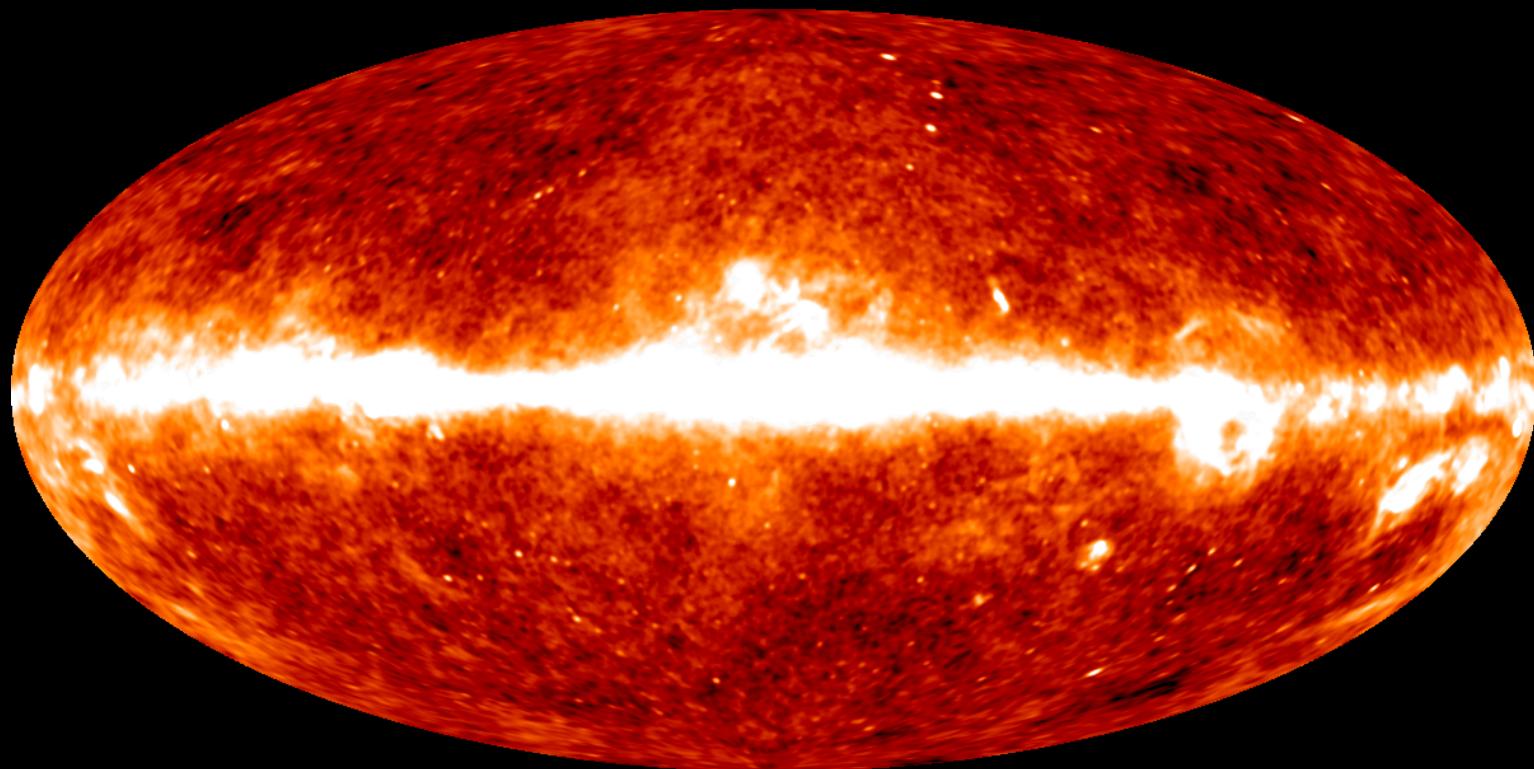


from hazes to bubbles:

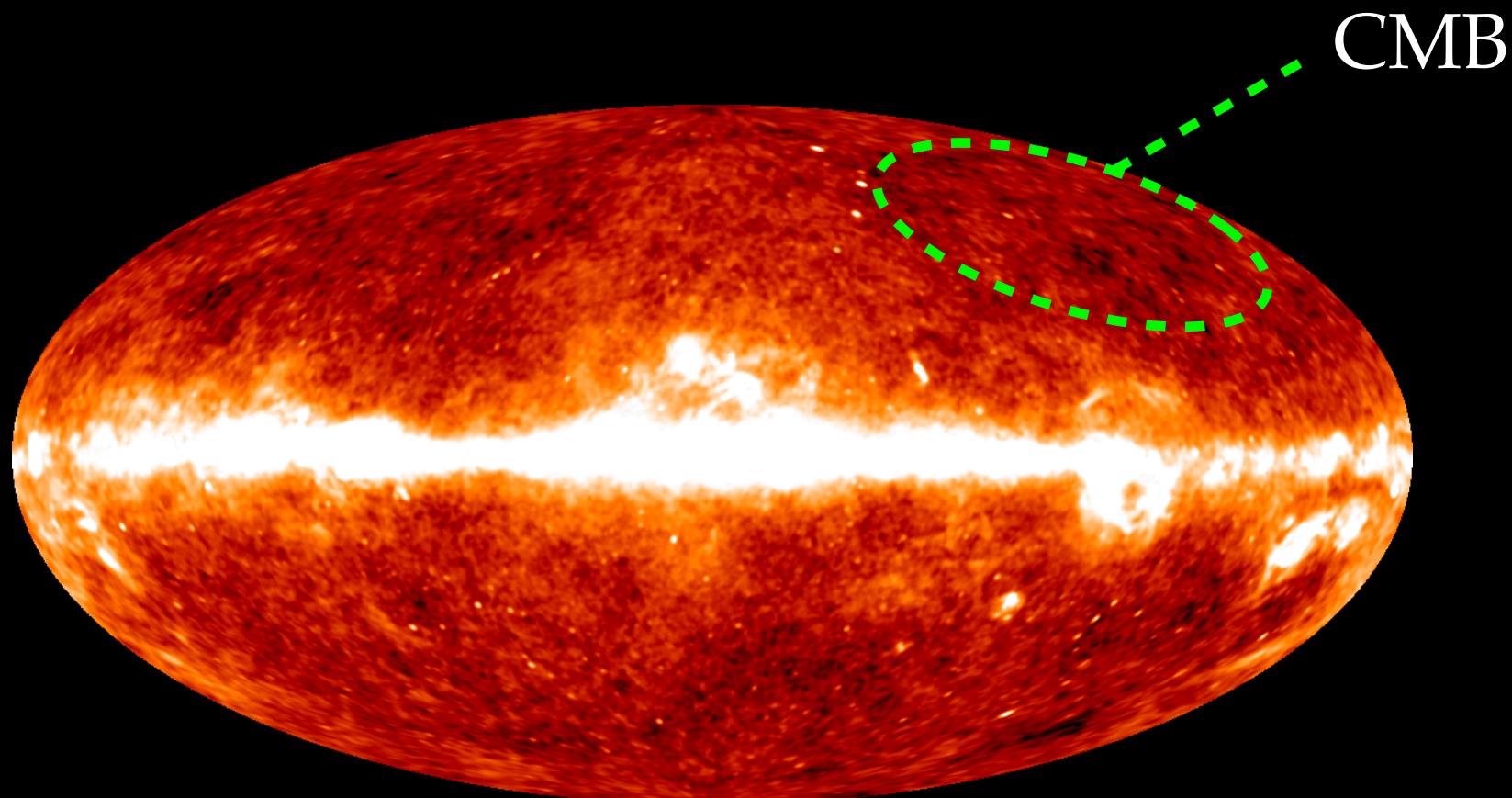
*an enormous eruption from the heart
of the Milky Way...*

microwaves...



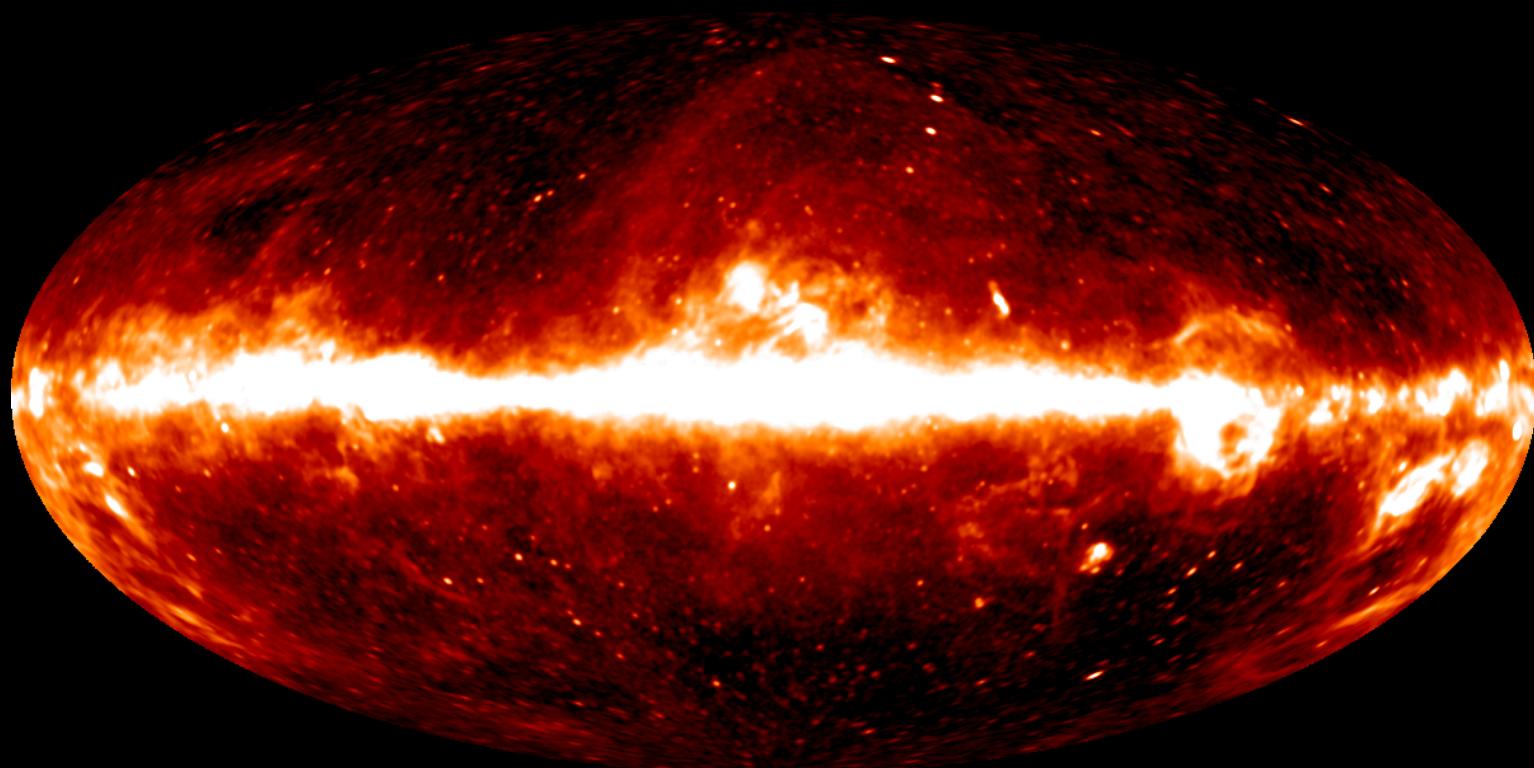
WMAP 23 GHz

microwaves...



WMAP 23 GHz

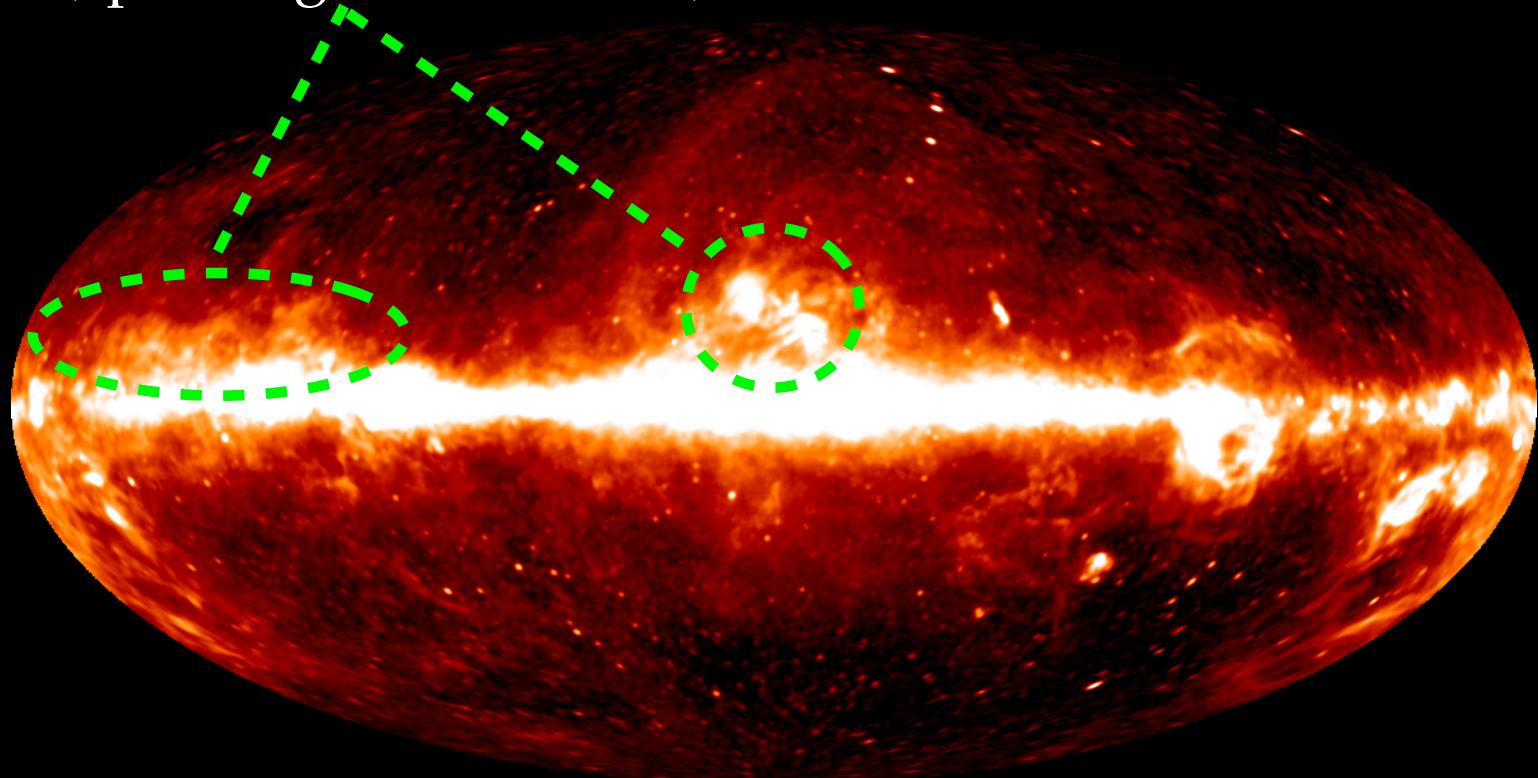
microwaves...



WMAP 23 GHz

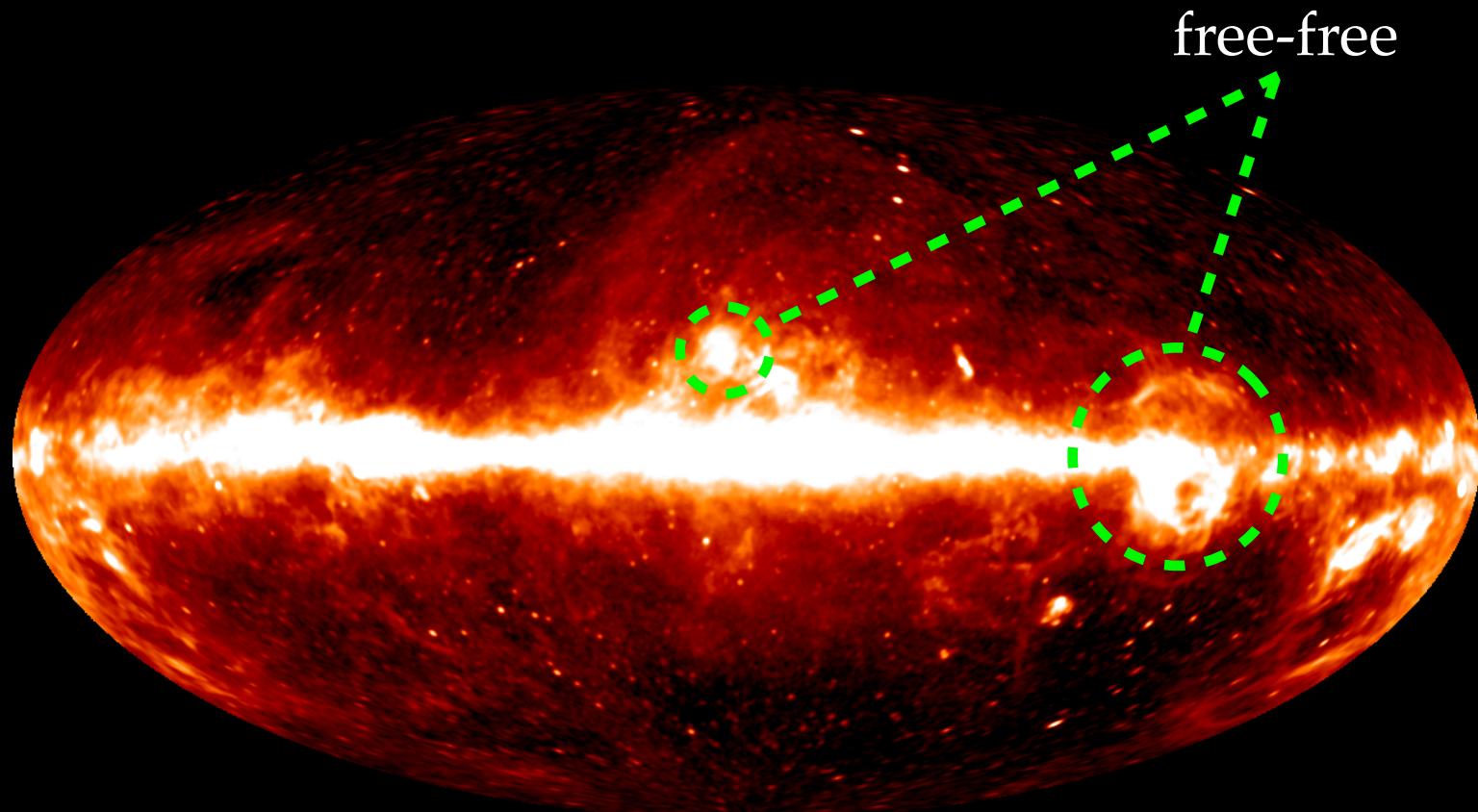
microwaves...

dust (spinning and thermal)



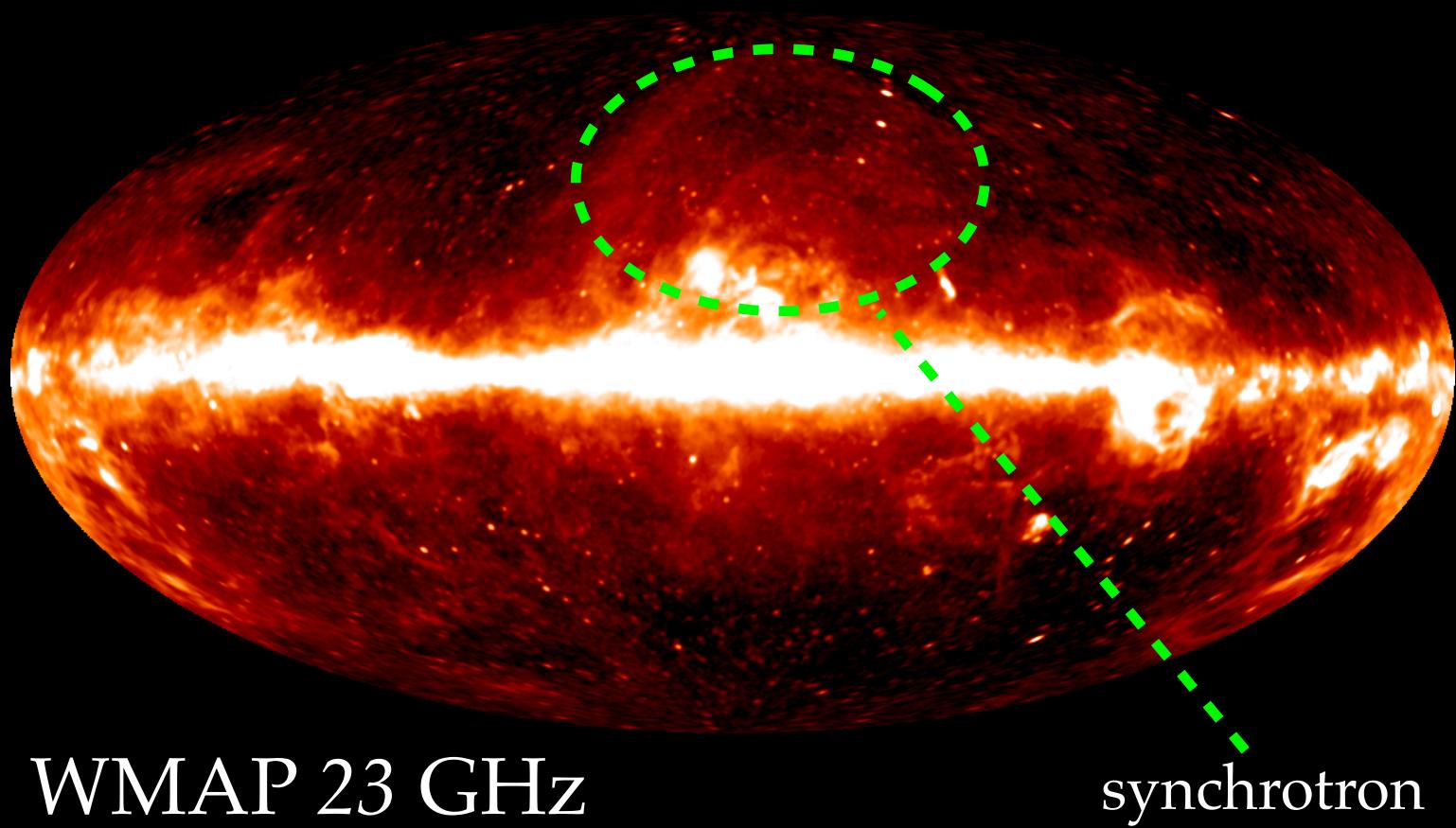
WMAP 23 GHz

microwaves...

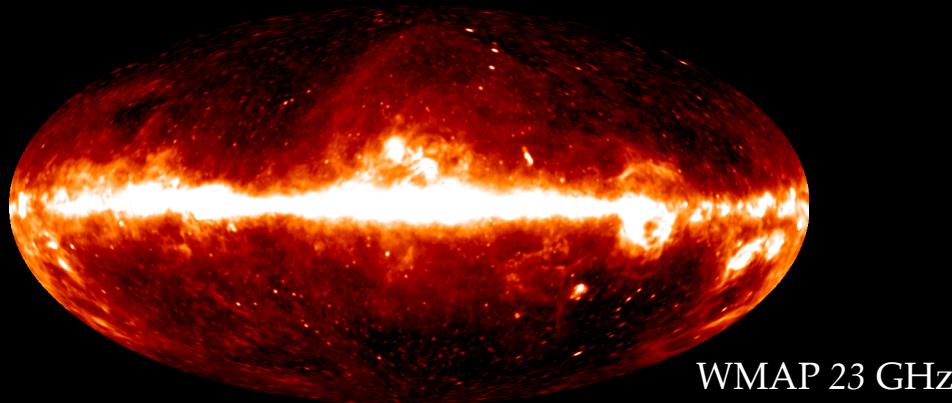


WMAP 23 GHz

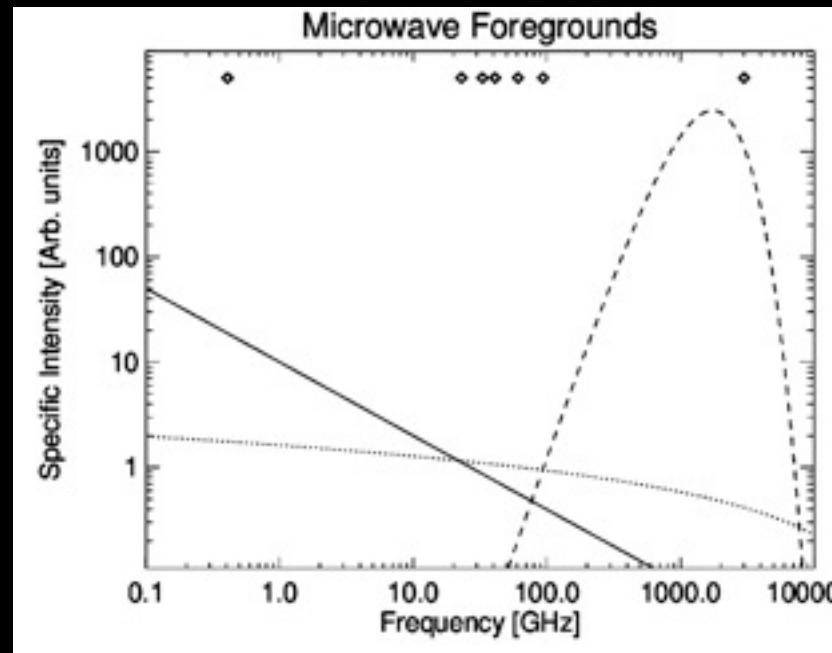
microwaves...



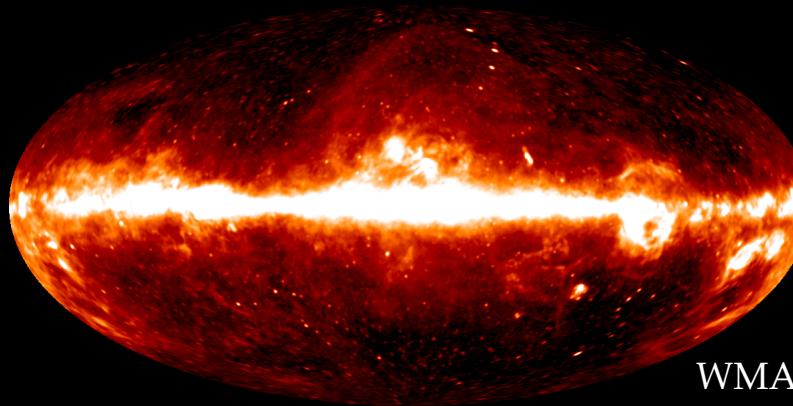
microwaves...



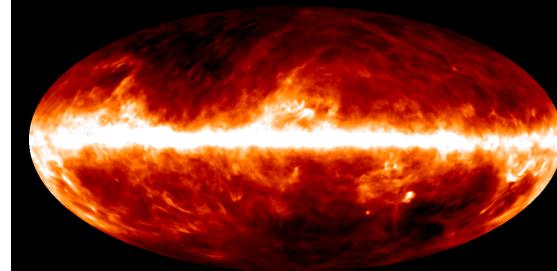
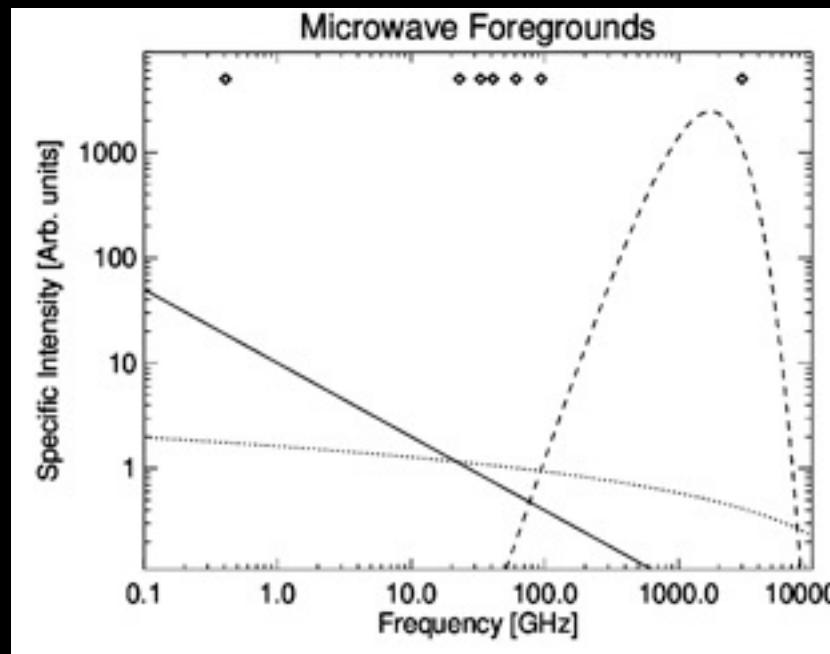
WMAP 23 GHz



microwaves...

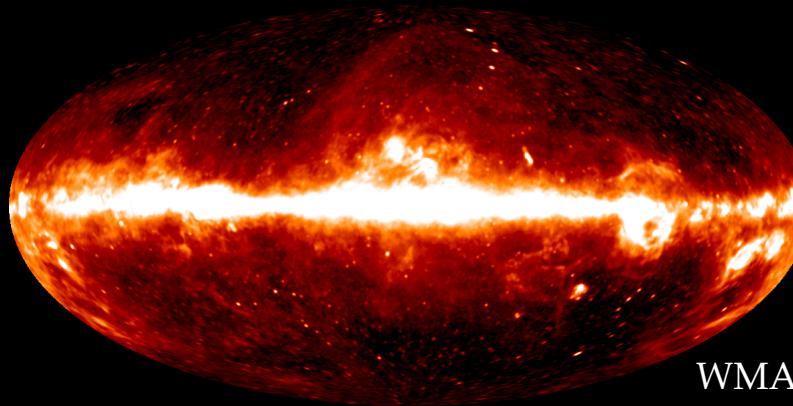


WMAP 23 GHz

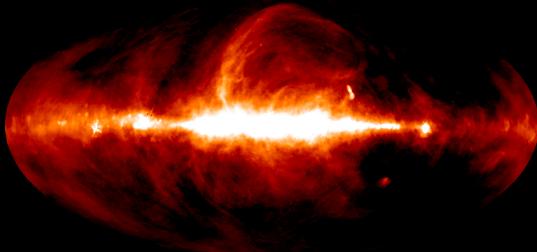


Schlegel *et al.* (1998)

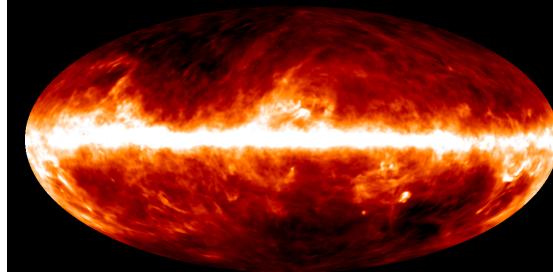
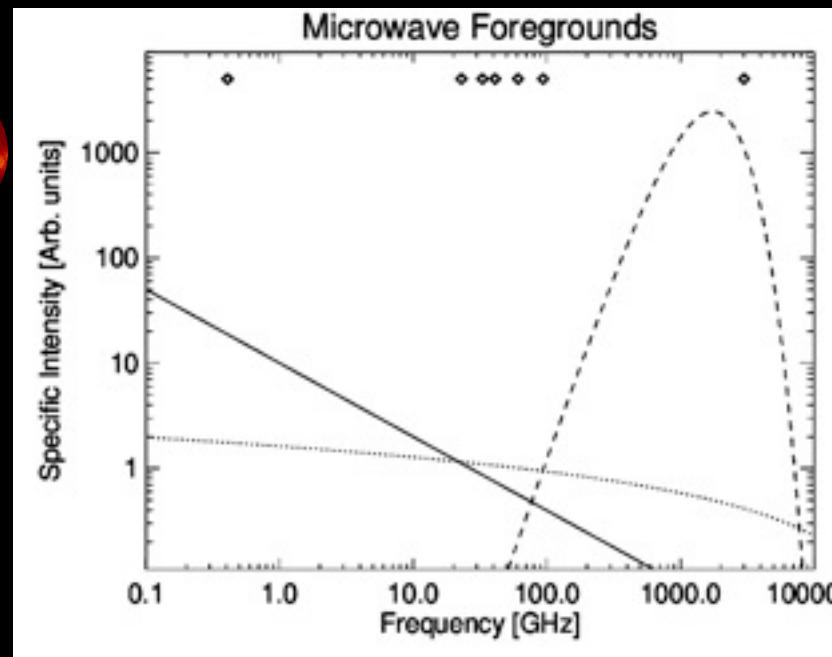
microwaves...



WMAP 23 GHz

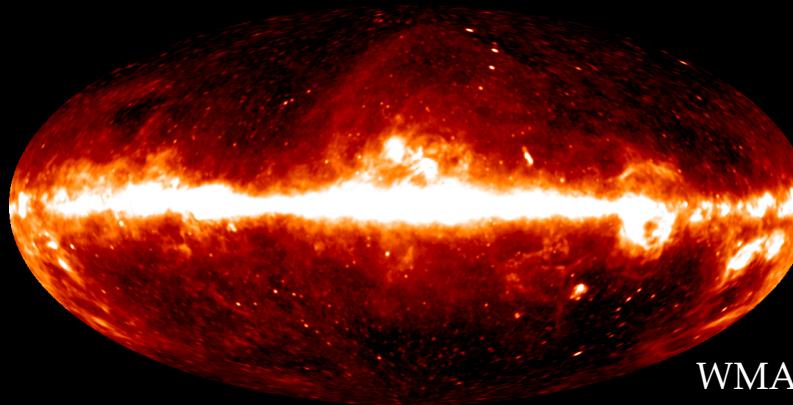


Haslam *et al.* (1982)

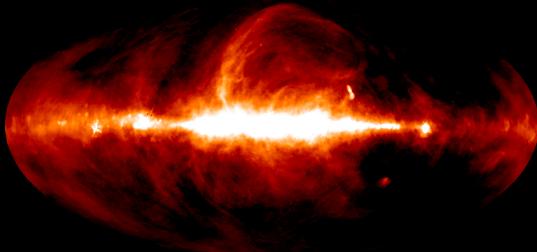


Schlegel *et al.* (1998)

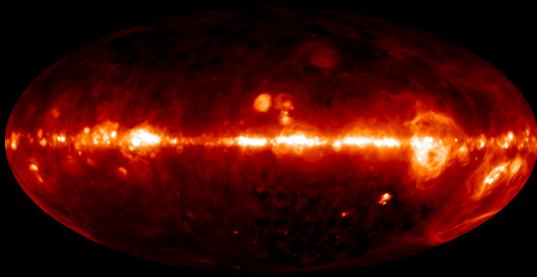
microwaves...



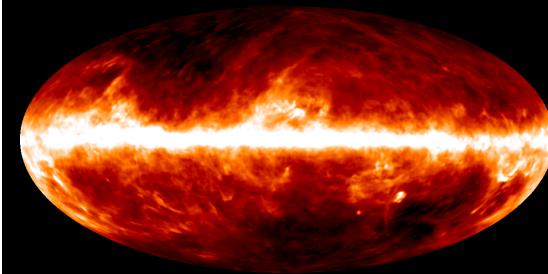
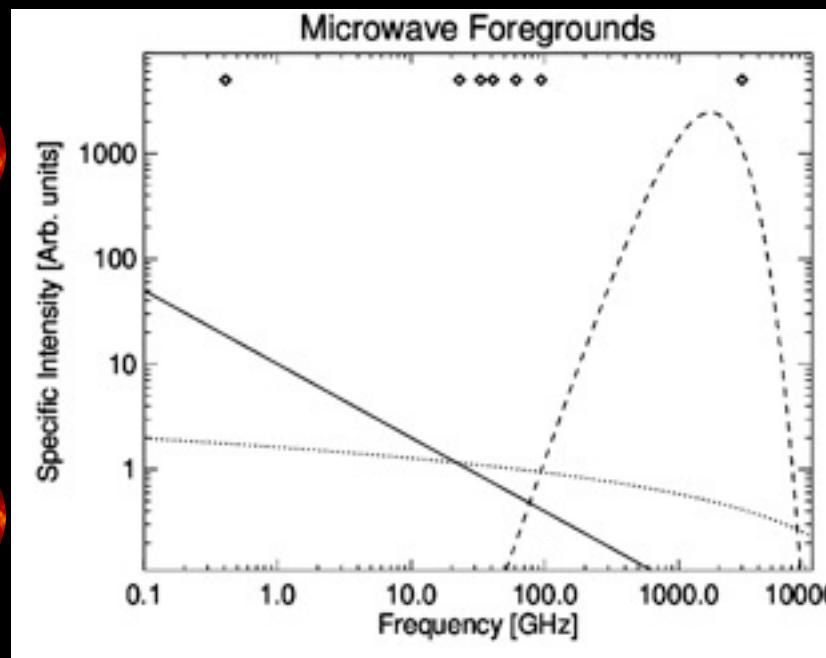
WMAP 23 GHz



Haslam *et al.* (1982)



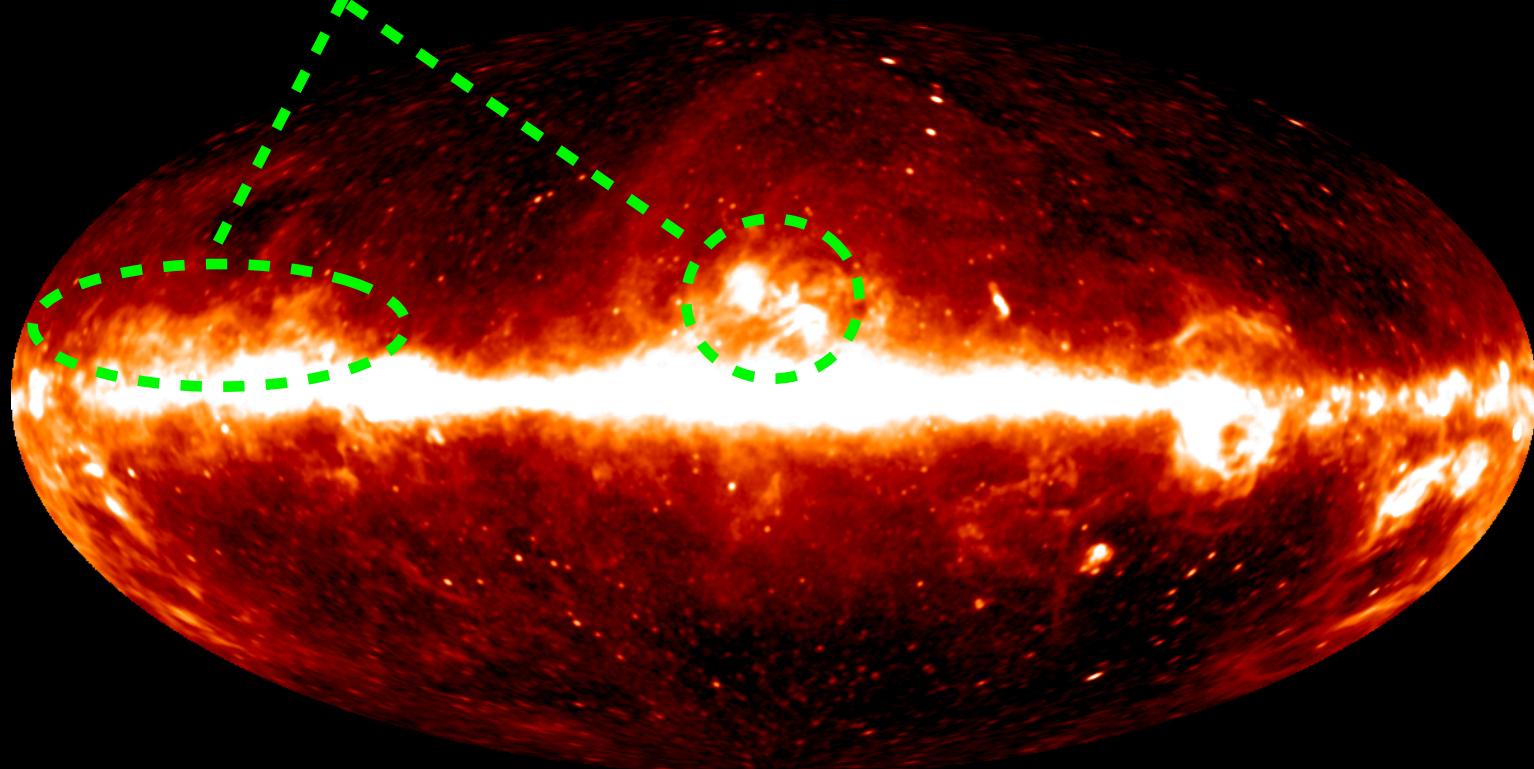
H α (Finkbeiner, 2003)



Schlegel *et al.* (1998)

microwaves...

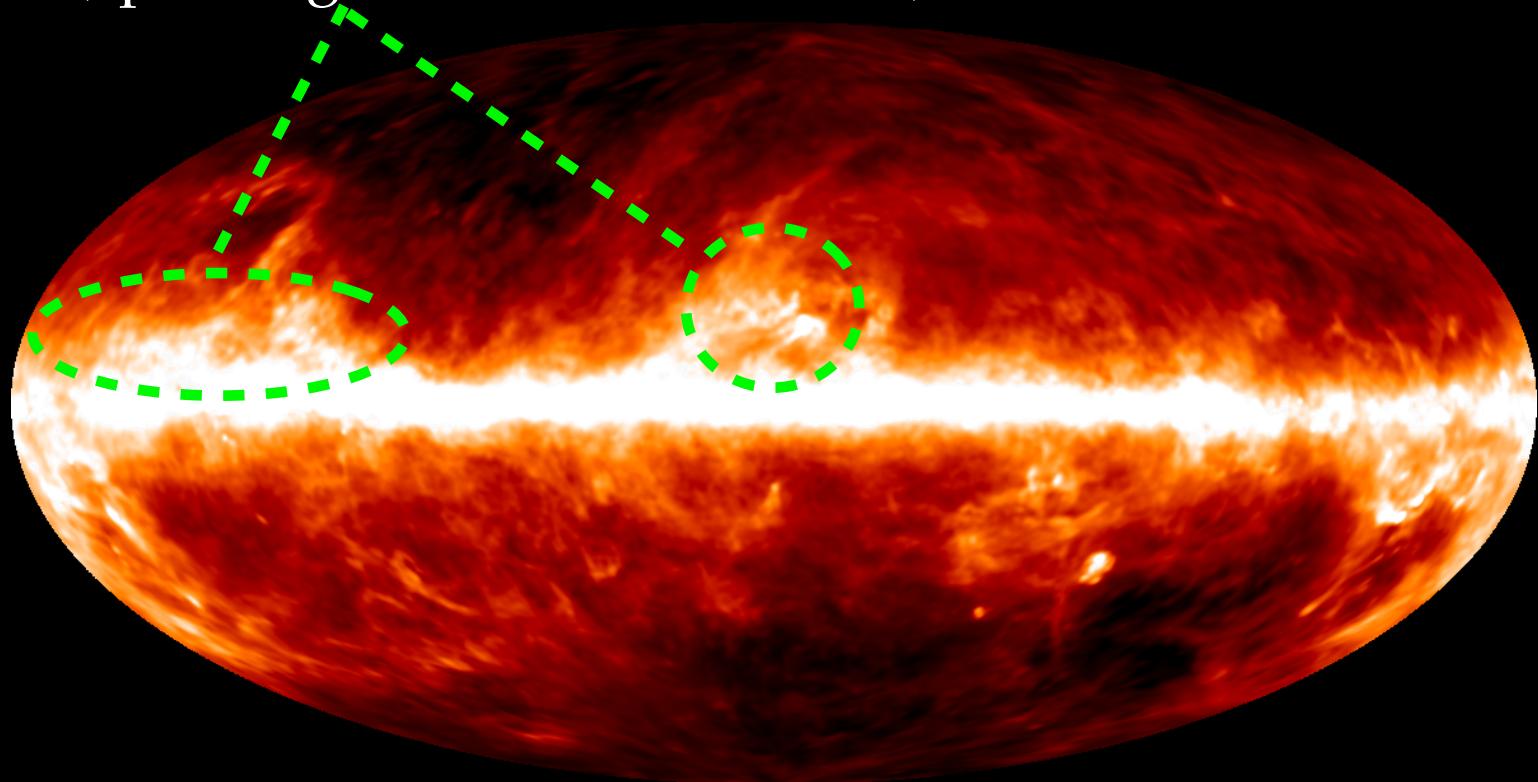
dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)



WMAP 23 GHz

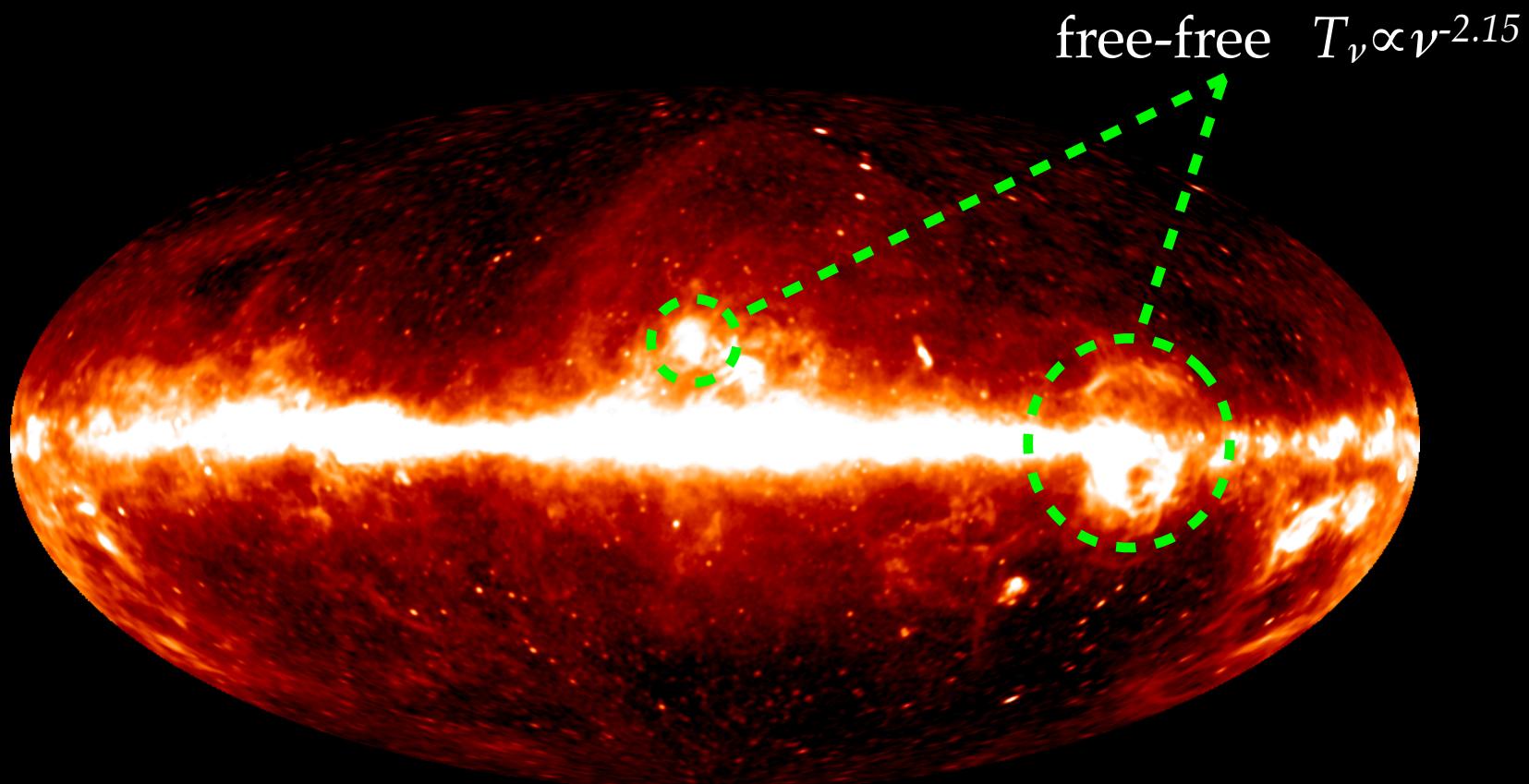
microwaves...

dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)



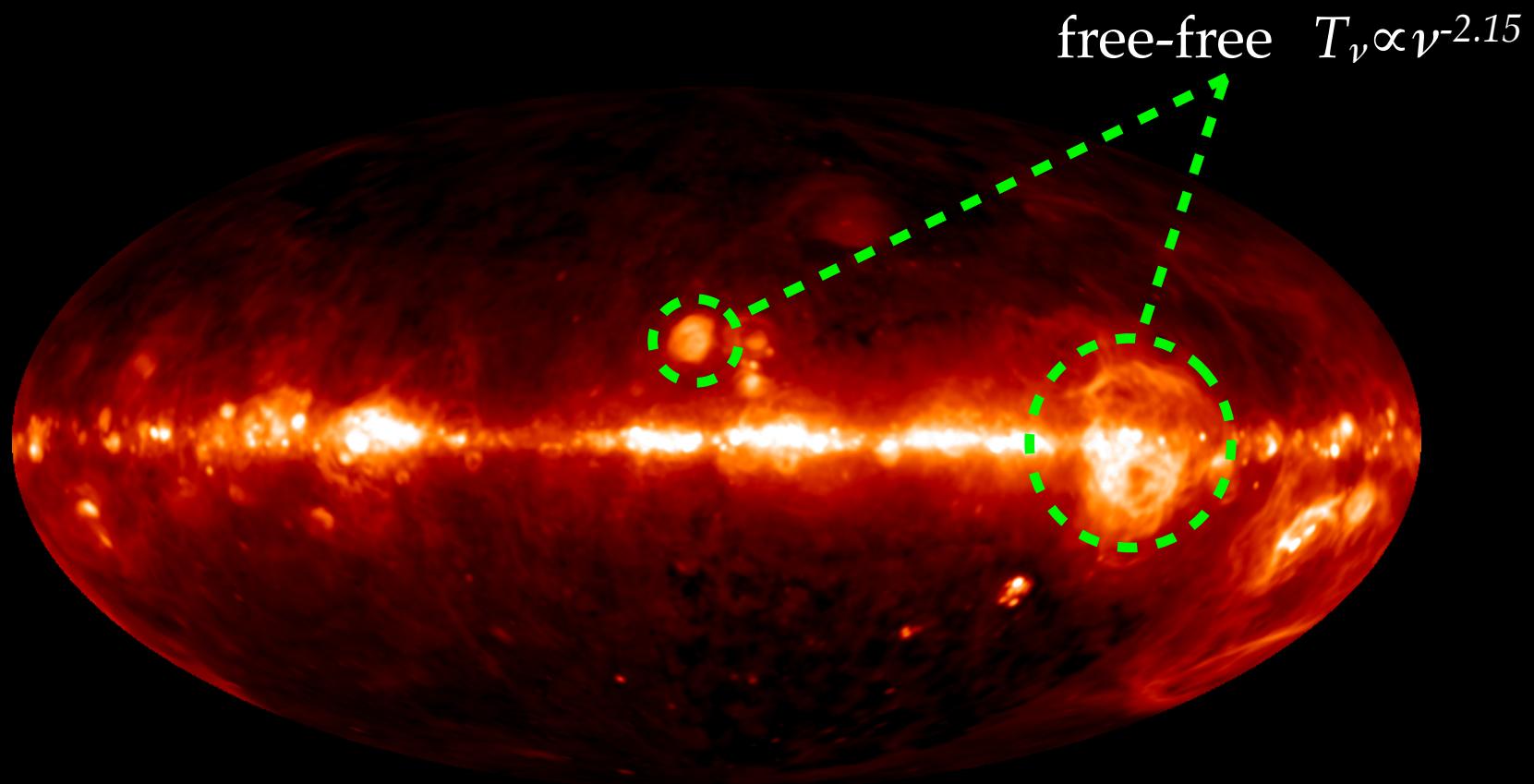
Finkbeiner, Davis, & Schlegel (1999)

microwaves...



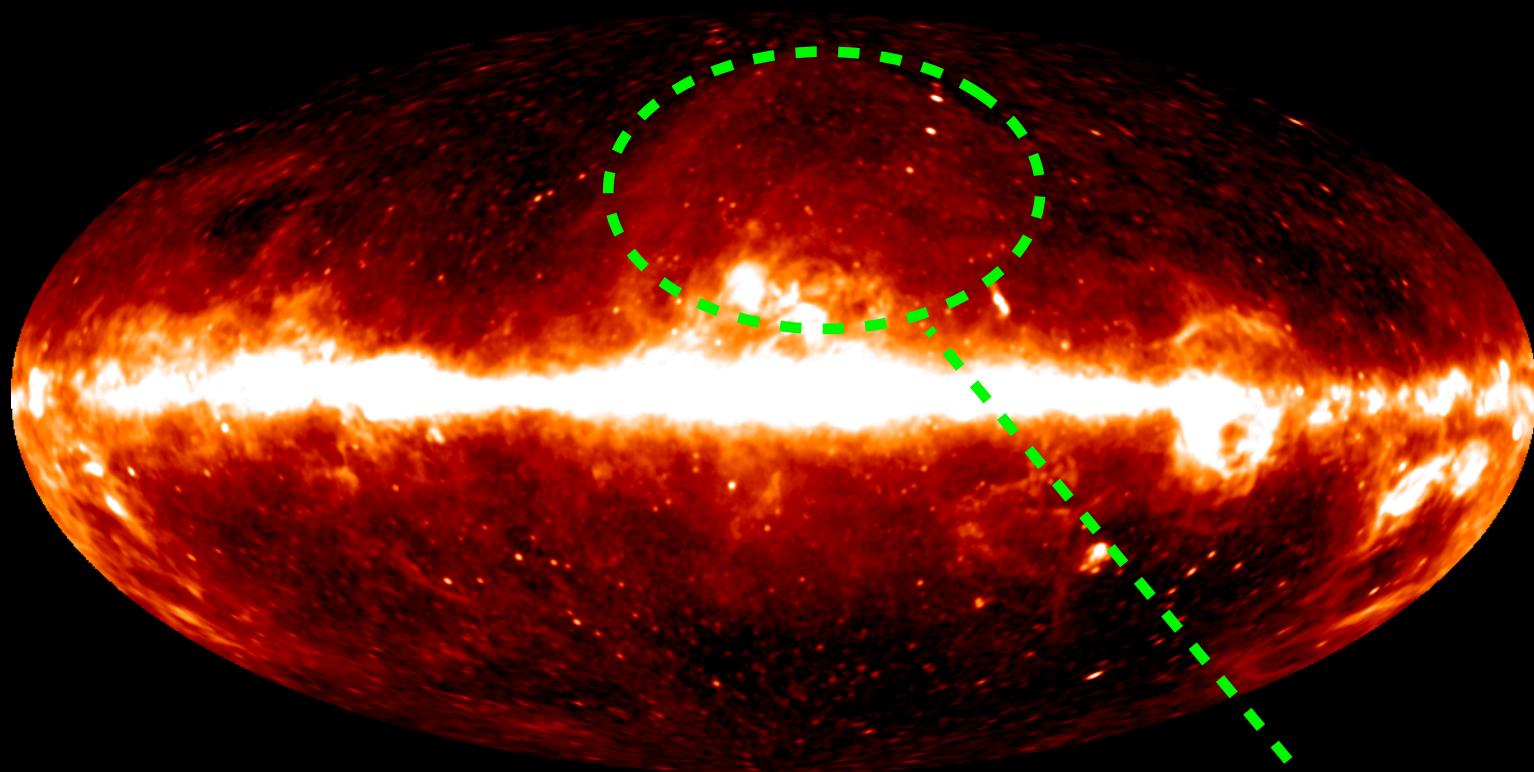
WMAP 23 GHz

microwaves...



Finkbeiner (2003)

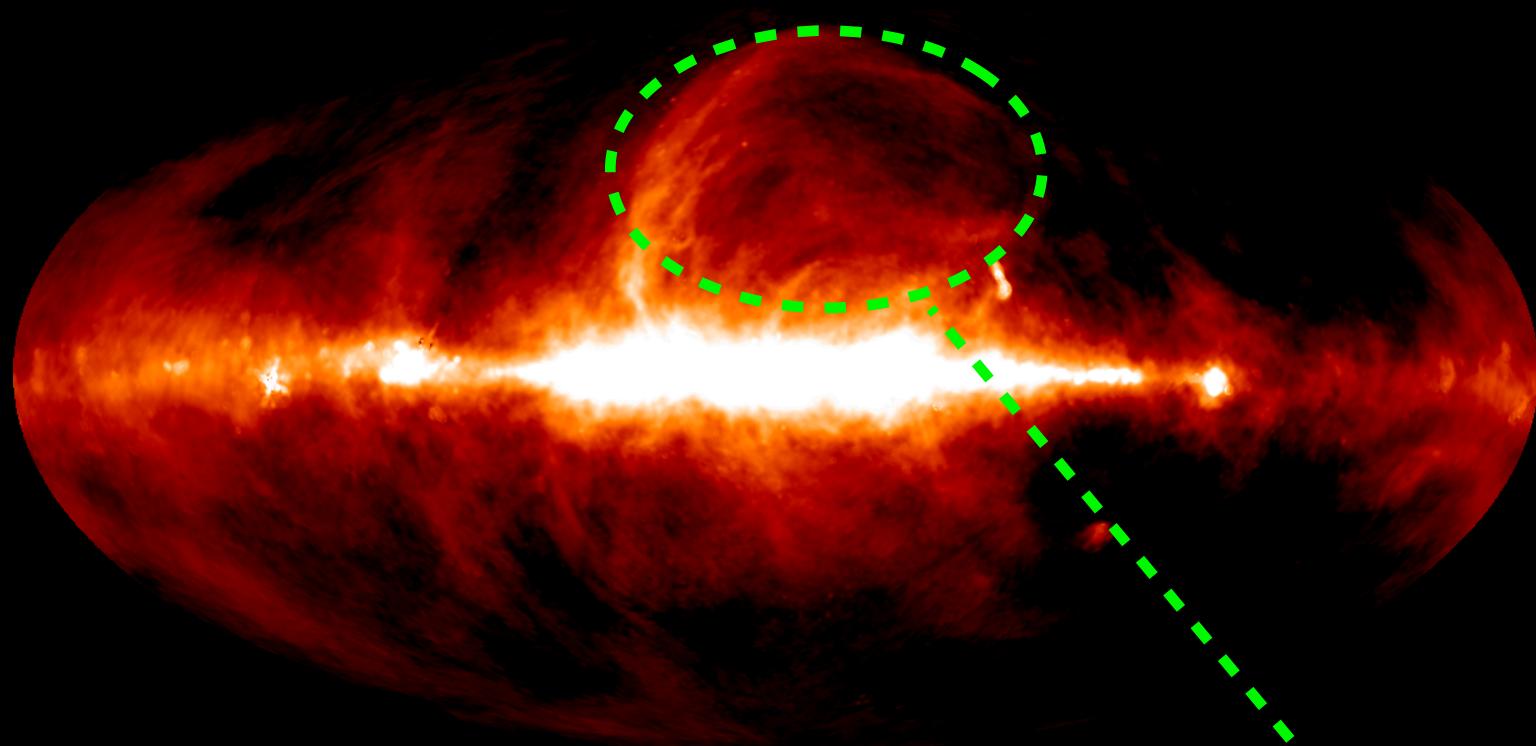
microwaves...



WMAP 23 GHz

synchrotron $T_\nu \propto \nu^{-3.0}$

microwaves...



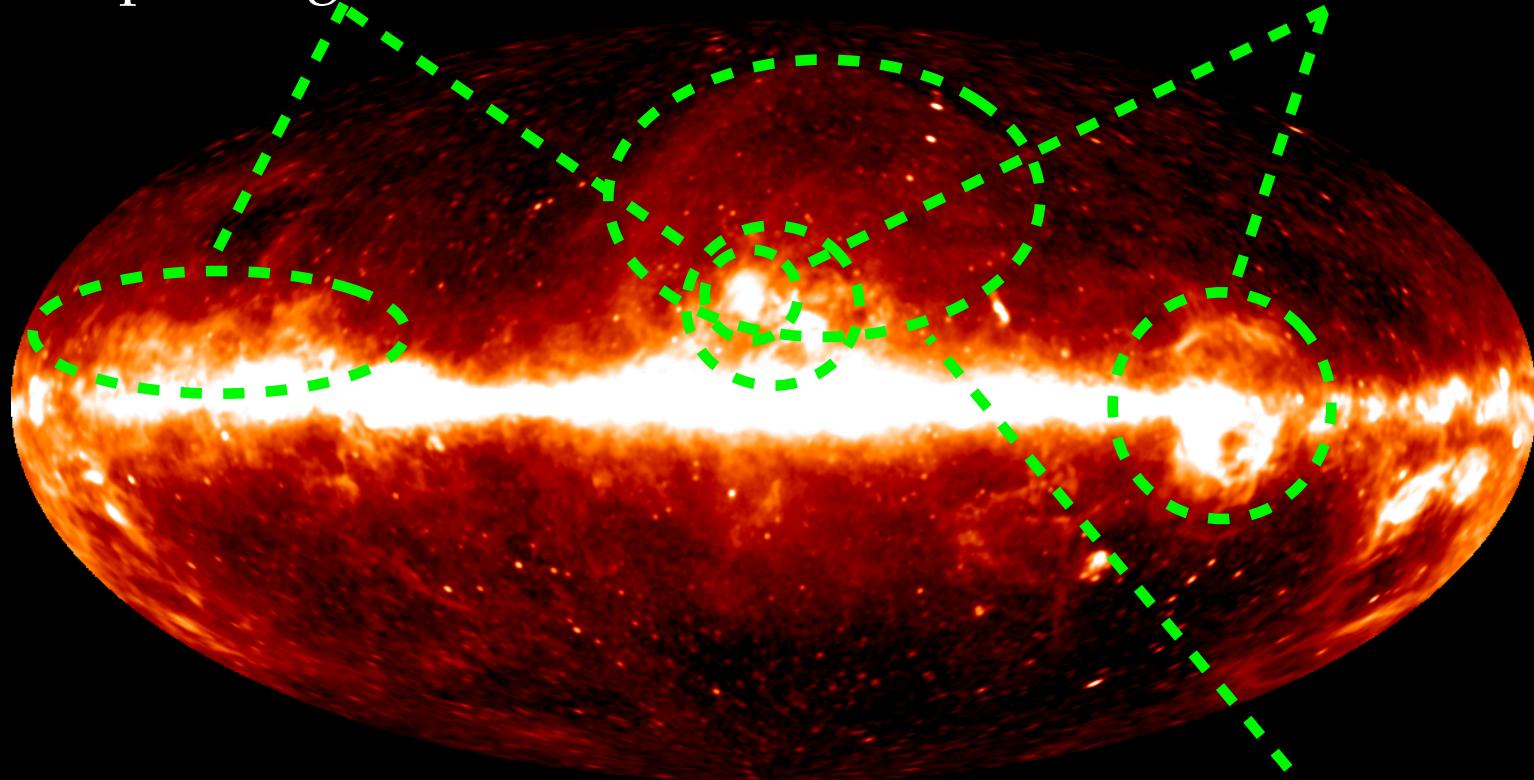
Haslam et al. (1982)

synchrotron $T_\nu \propto \nu^{-3.0}$

microwaves...

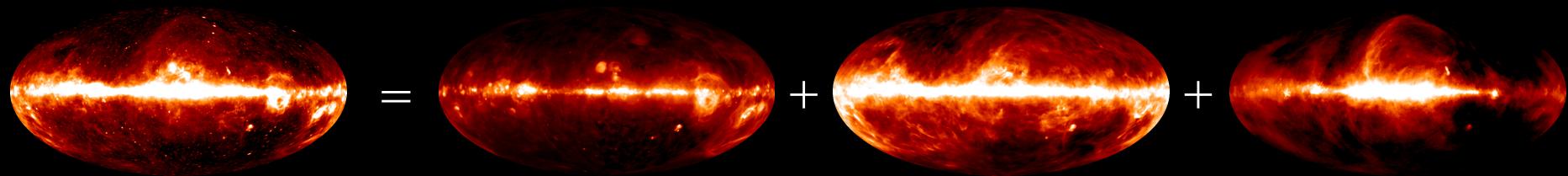
dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)

free-free $T_\nu \propto \nu^{-2.15}$



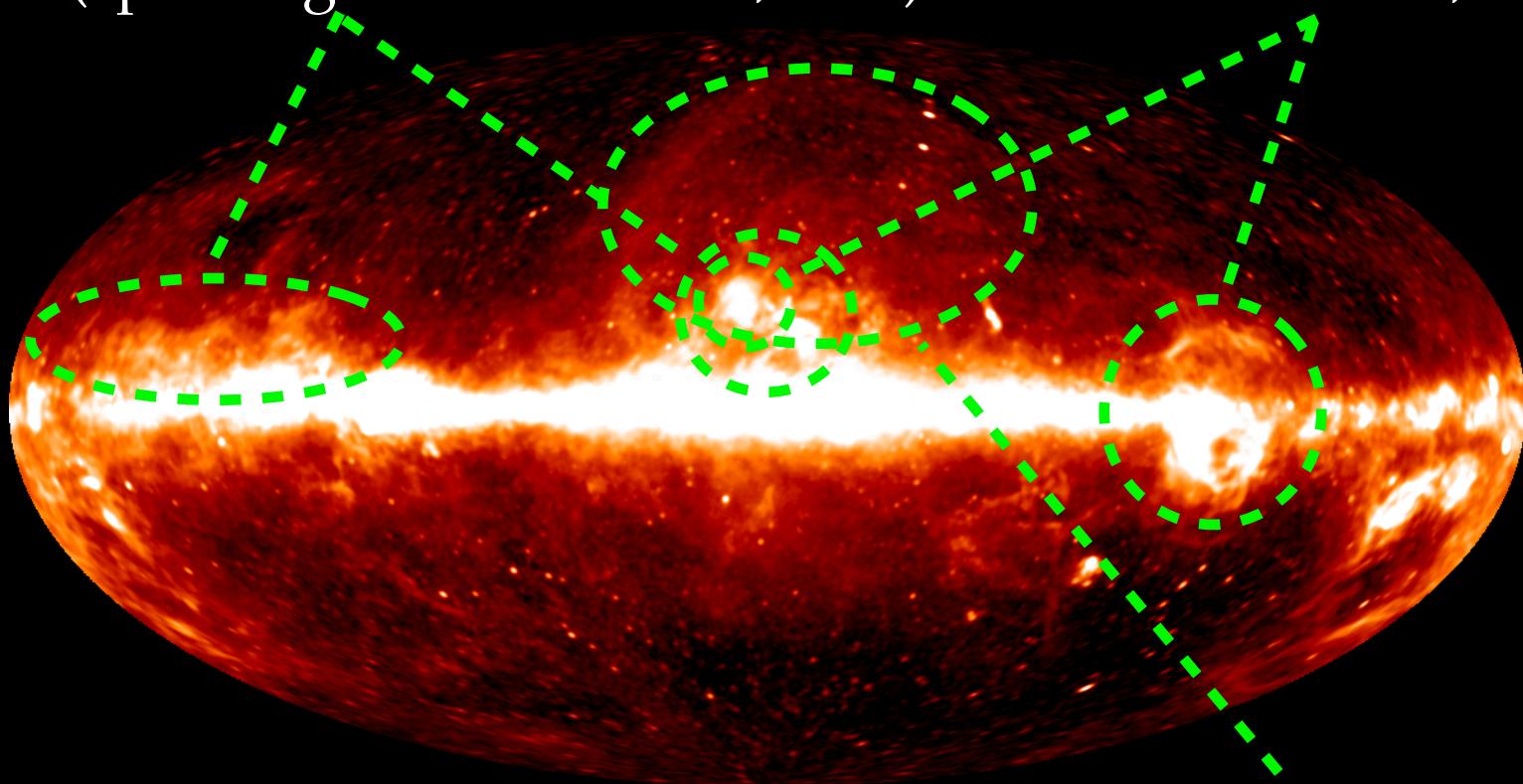
WMAP 23 GHz

synchrotron $T_\nu \propto \nu^{-3.0}$



dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)

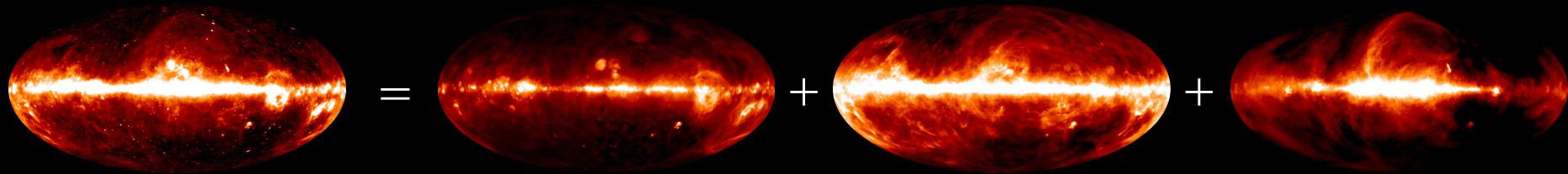
free-free $T_\nu \propto \nu^{-2.15}$



WMAP 23 GHz

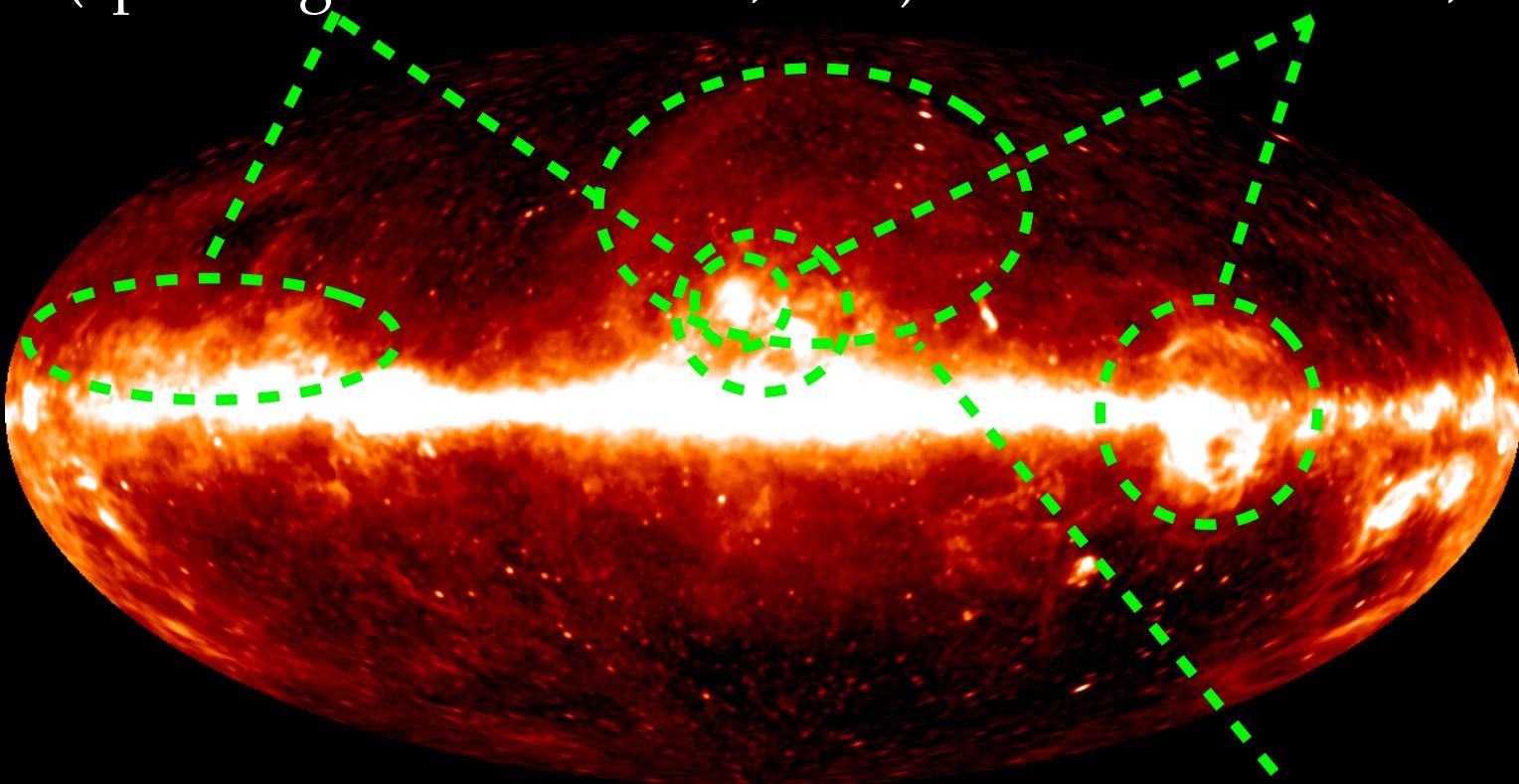
synchrotron $T_\nu \propto \nu^{-3.0}$

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)

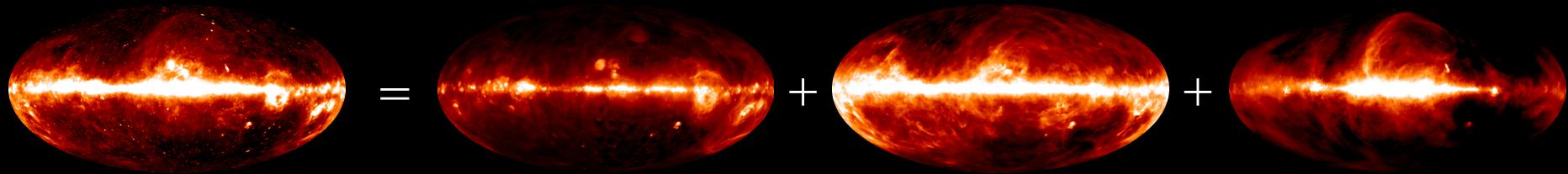
free-free $T_\nu \propto \nu^{-2.15}$



WMAP 23 GHz

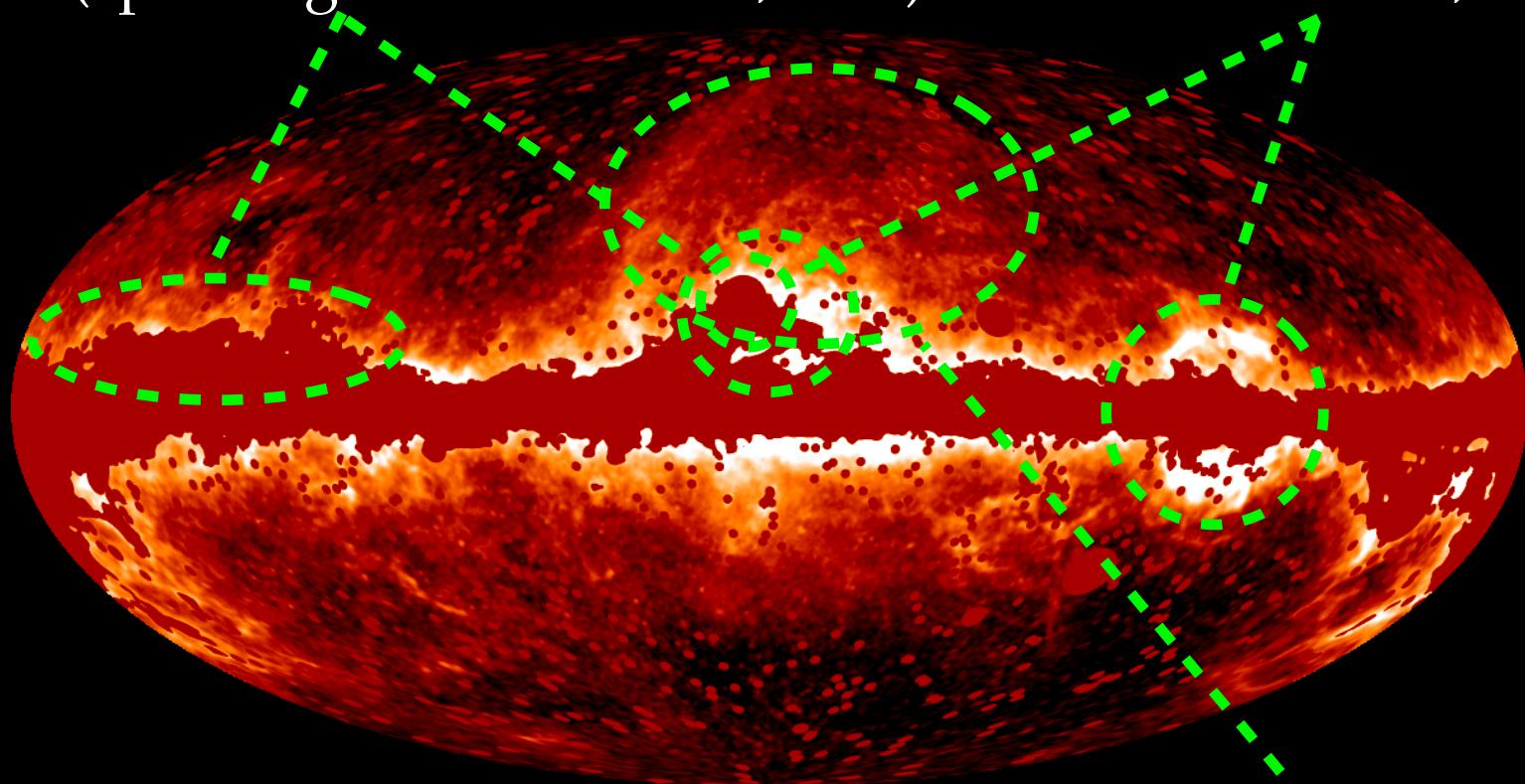
synchrotron $T_\nu \propto \nu^{-3.0}$

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



dust (spinning and thermal $T_\nu \propto \nu^{1.7}$)

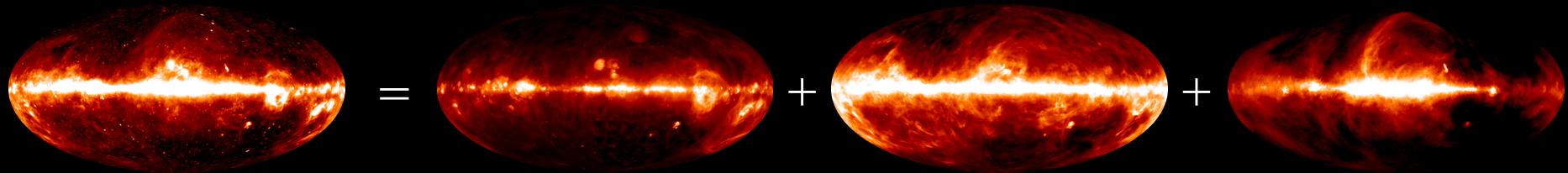
free-free $T_\nu \propto \nu^{-2.15}$



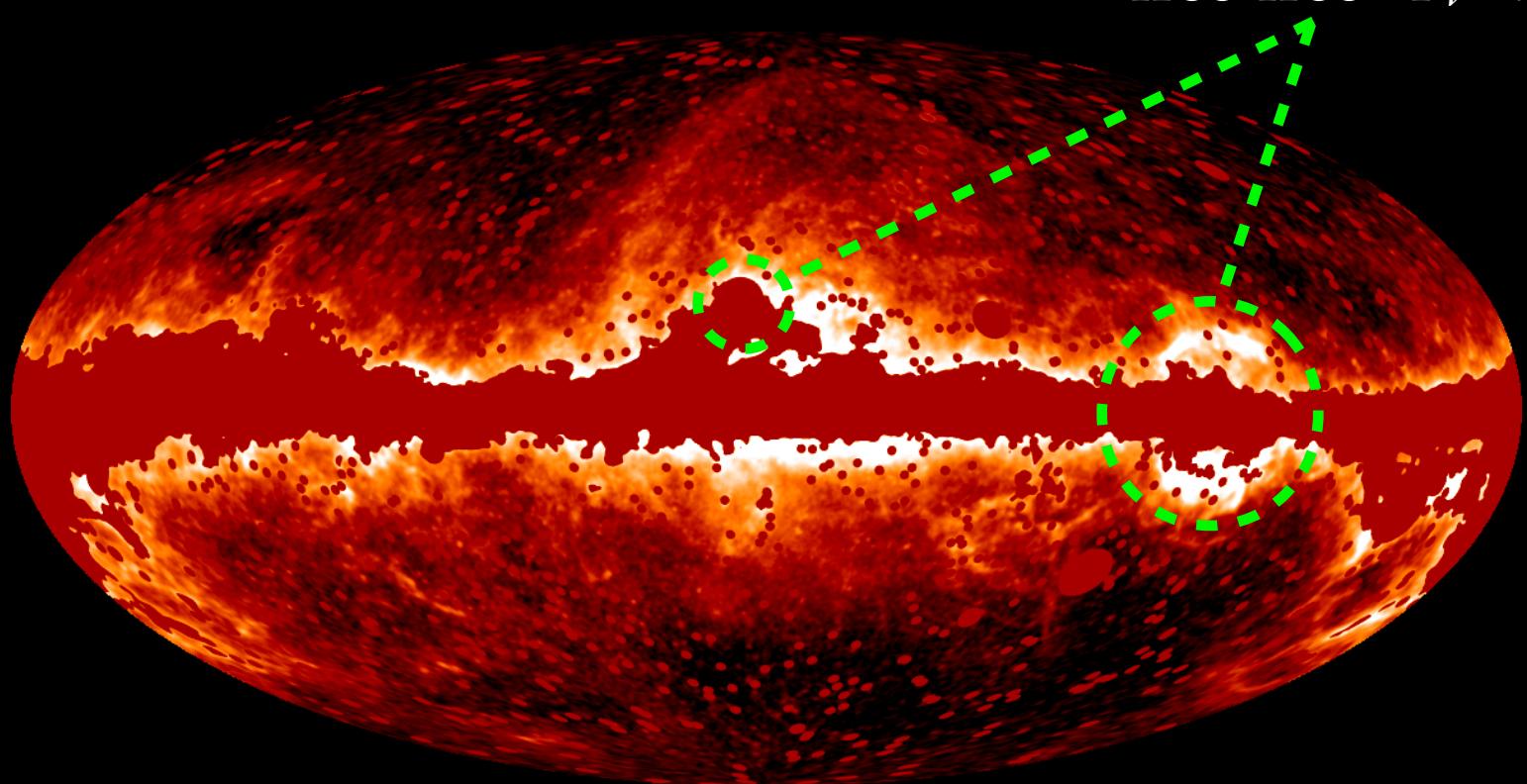
WMAP 23 GHz

synchrotron $T_\nu \propto \nu^{-3.0}$

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

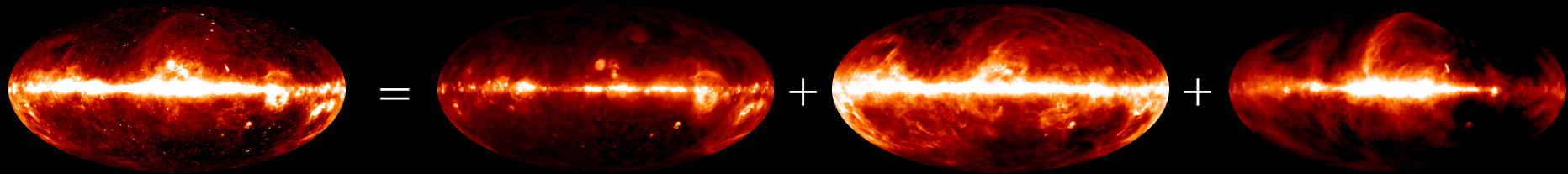


free-free $T_\nu \propto \nu^{-2.15}$

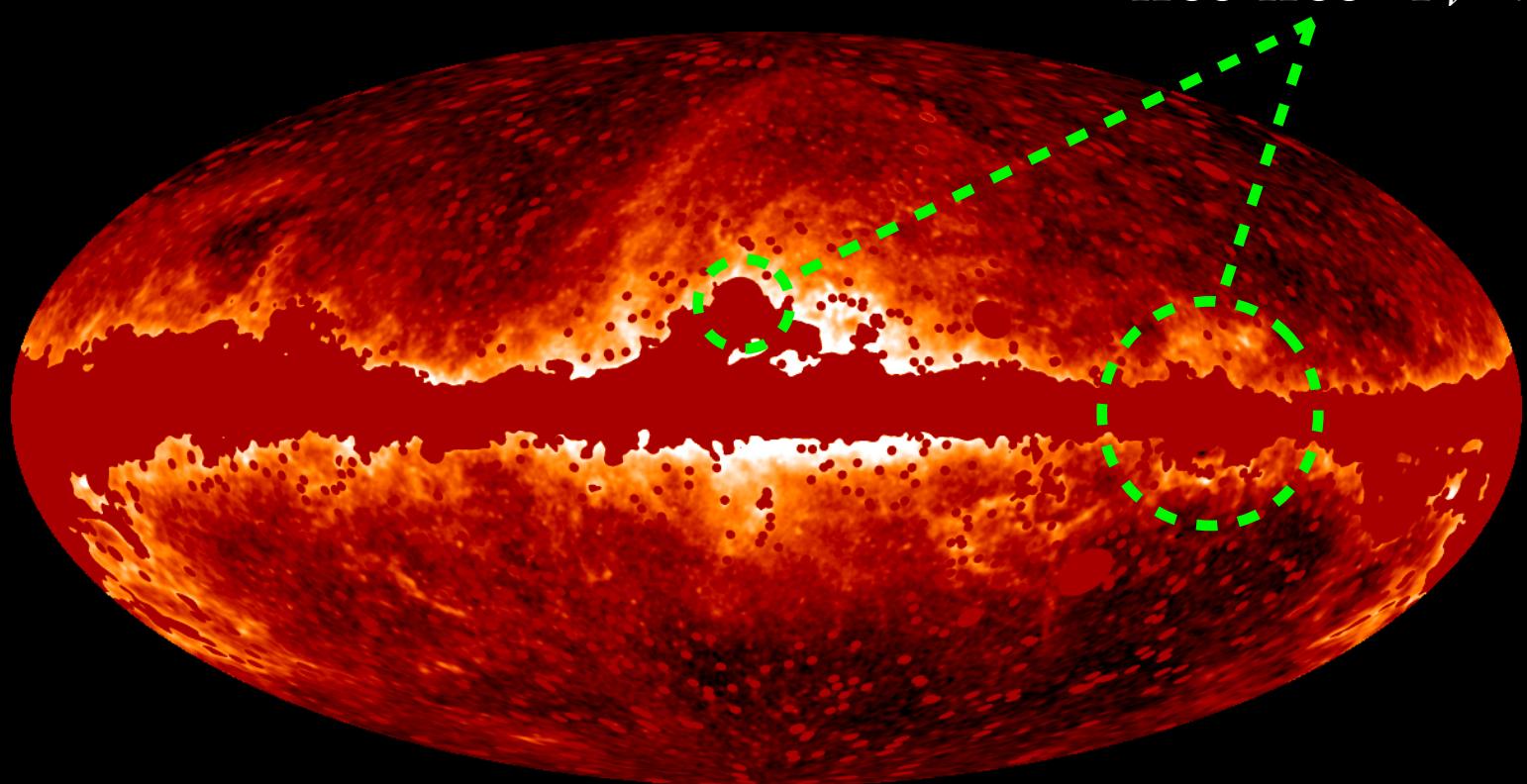


WMAP 23 GHz

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

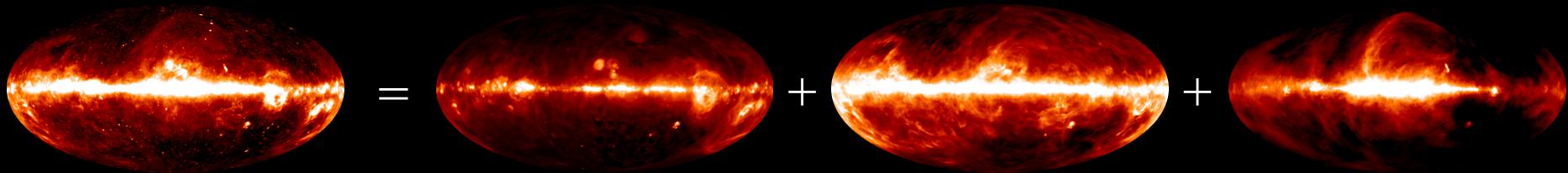


free-free $T_\nu \propto \nu^{-2.15}$

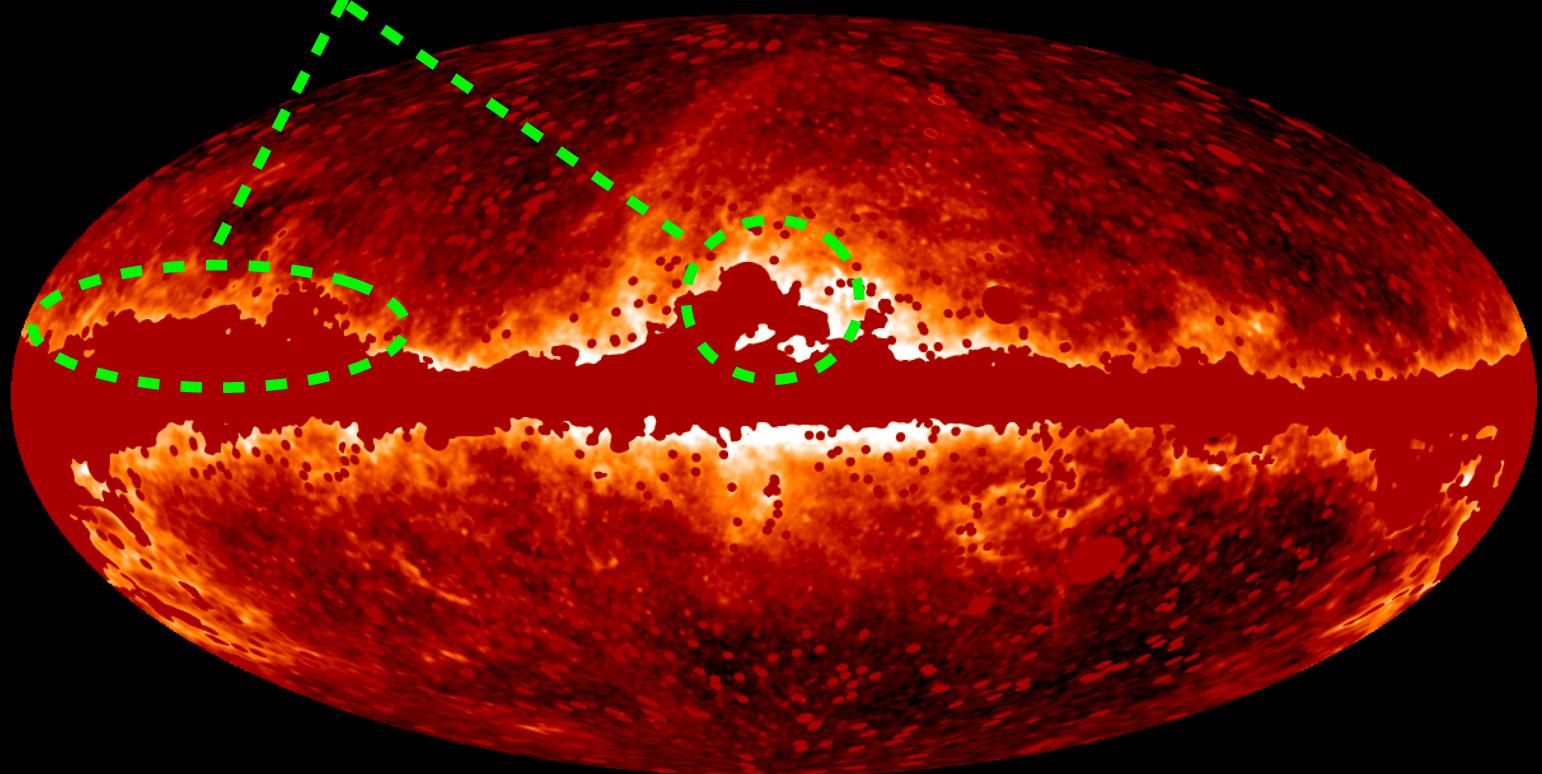


WMAP 23 GHz

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

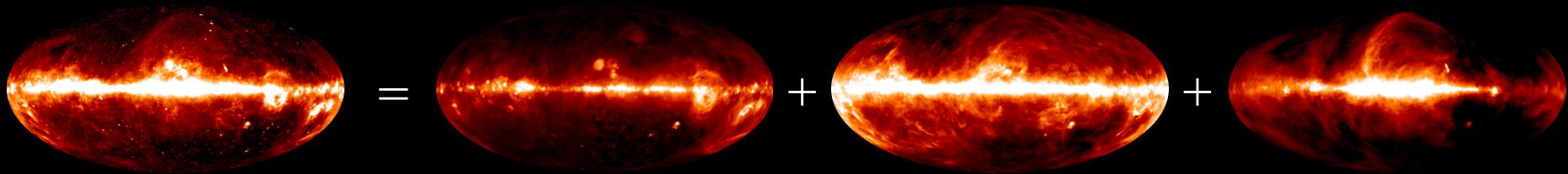


dust (spinning and thermal) $T_\nu \propto \nu^{1.7}$

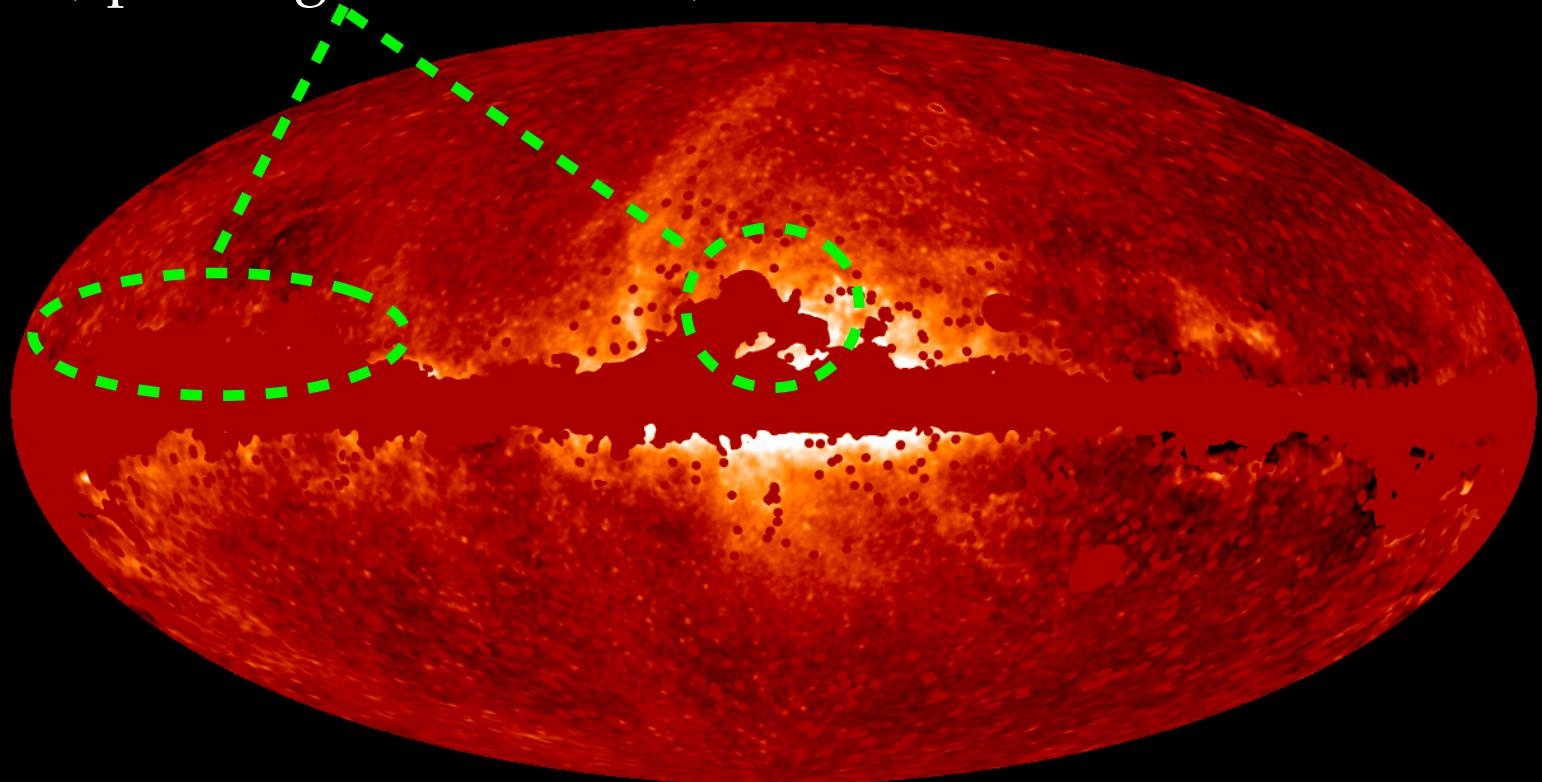


WMAP 23 GHz

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

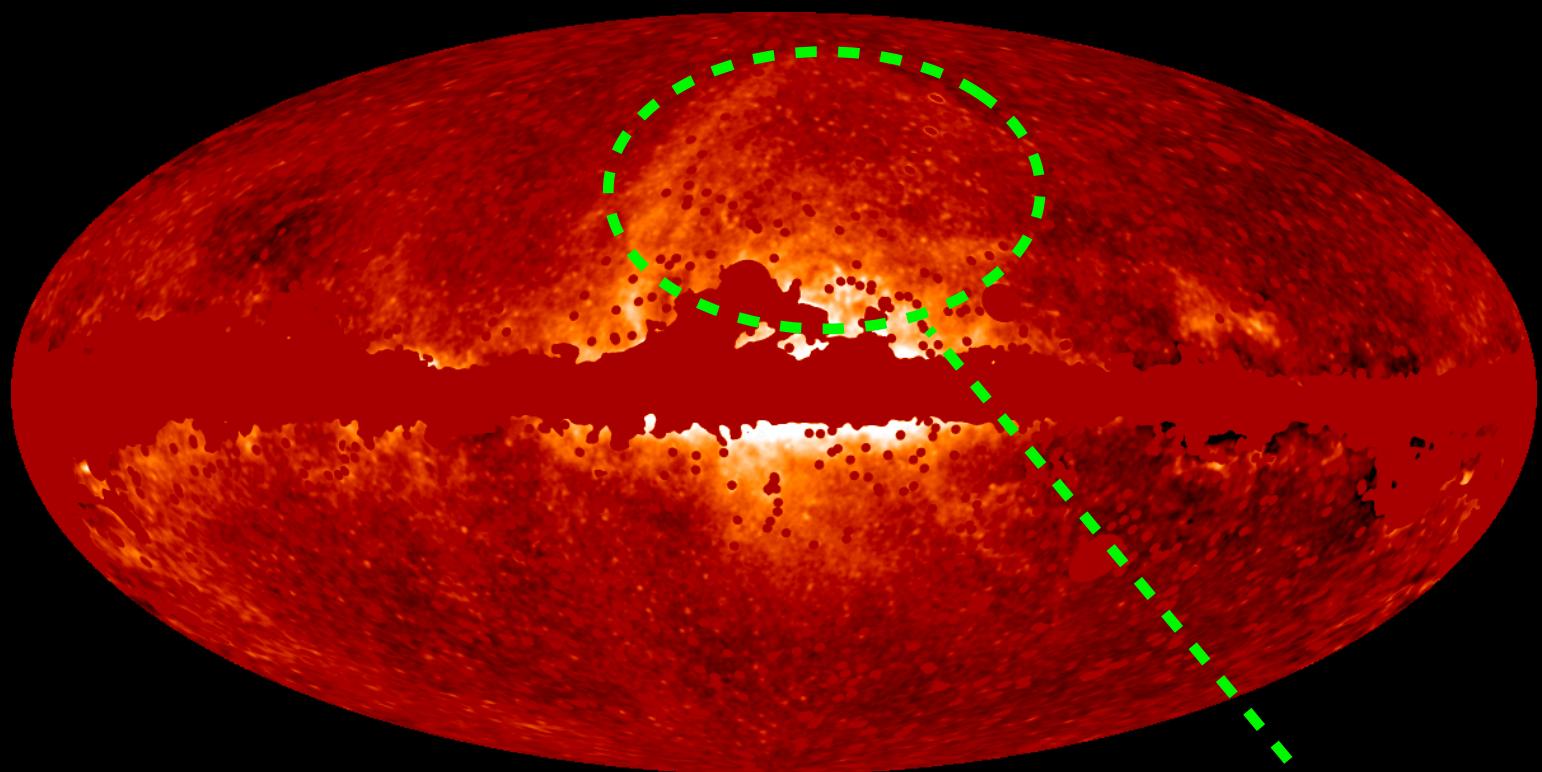
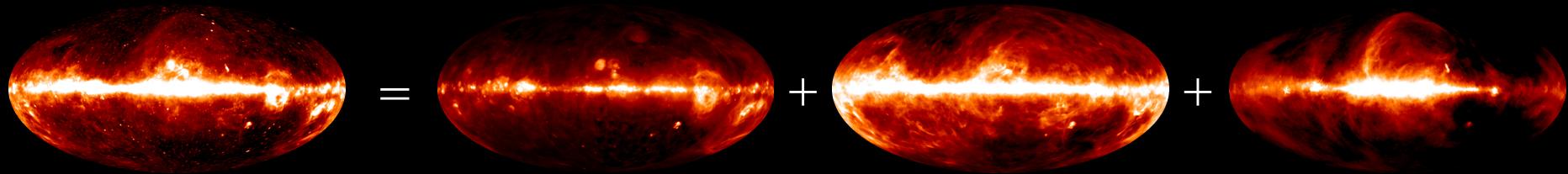


dust (spinning and thermal) $T_\nu \propto \nu^{1.7}$



WMAP 23 GHz

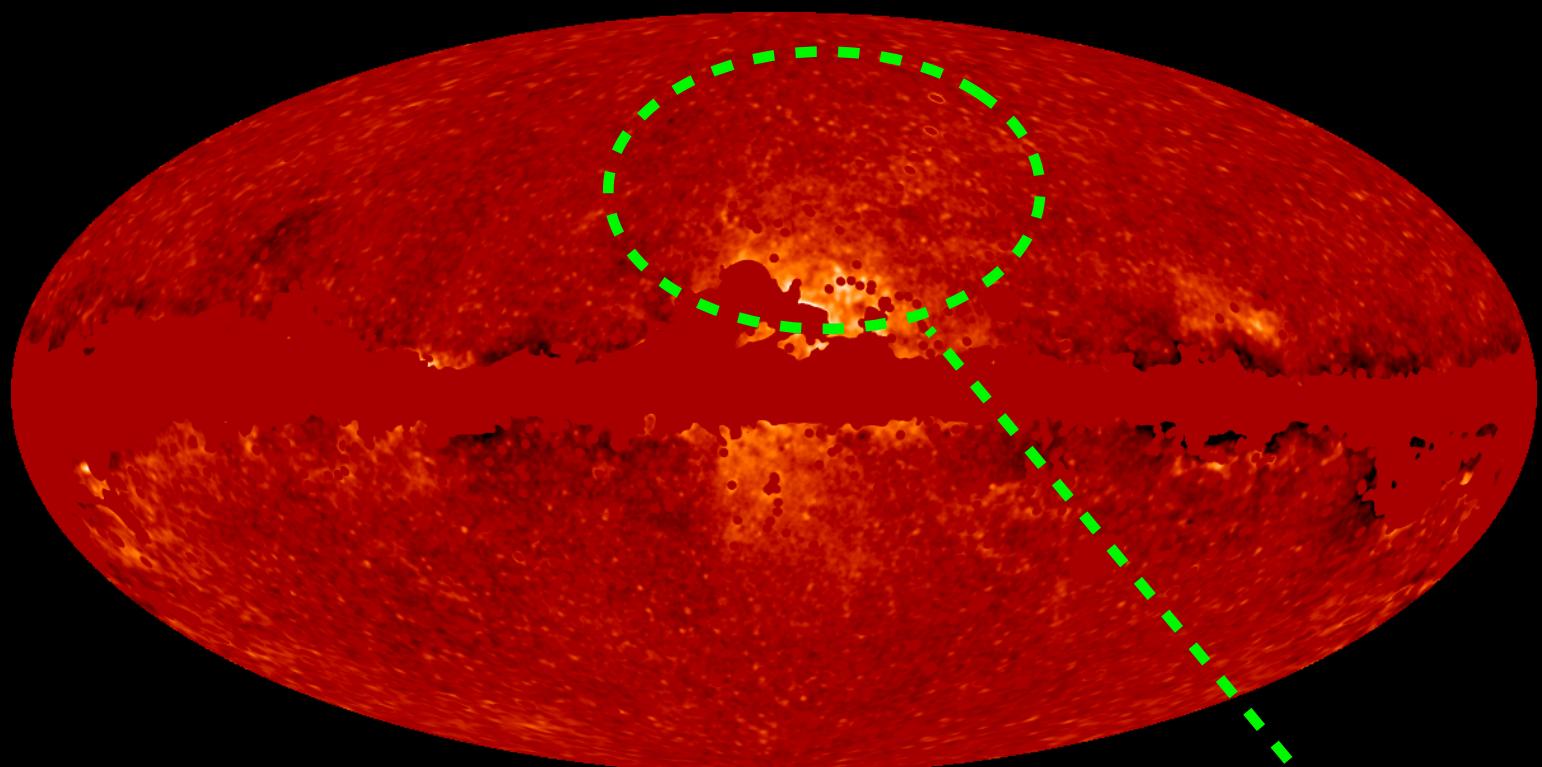
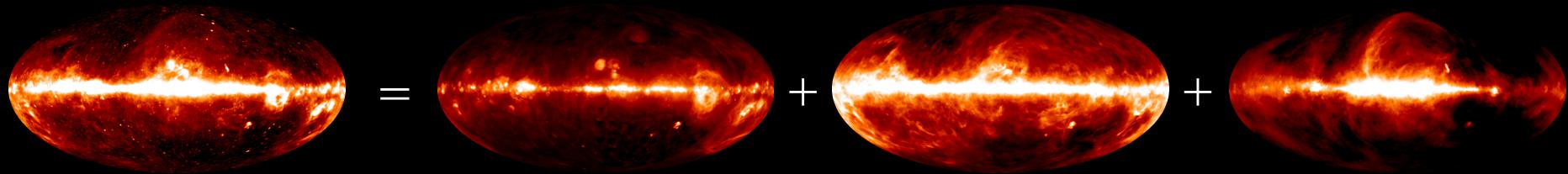
$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



WMAP 23 GHz

synchrotron $T_\nu \propto \nu^{-3.0}$

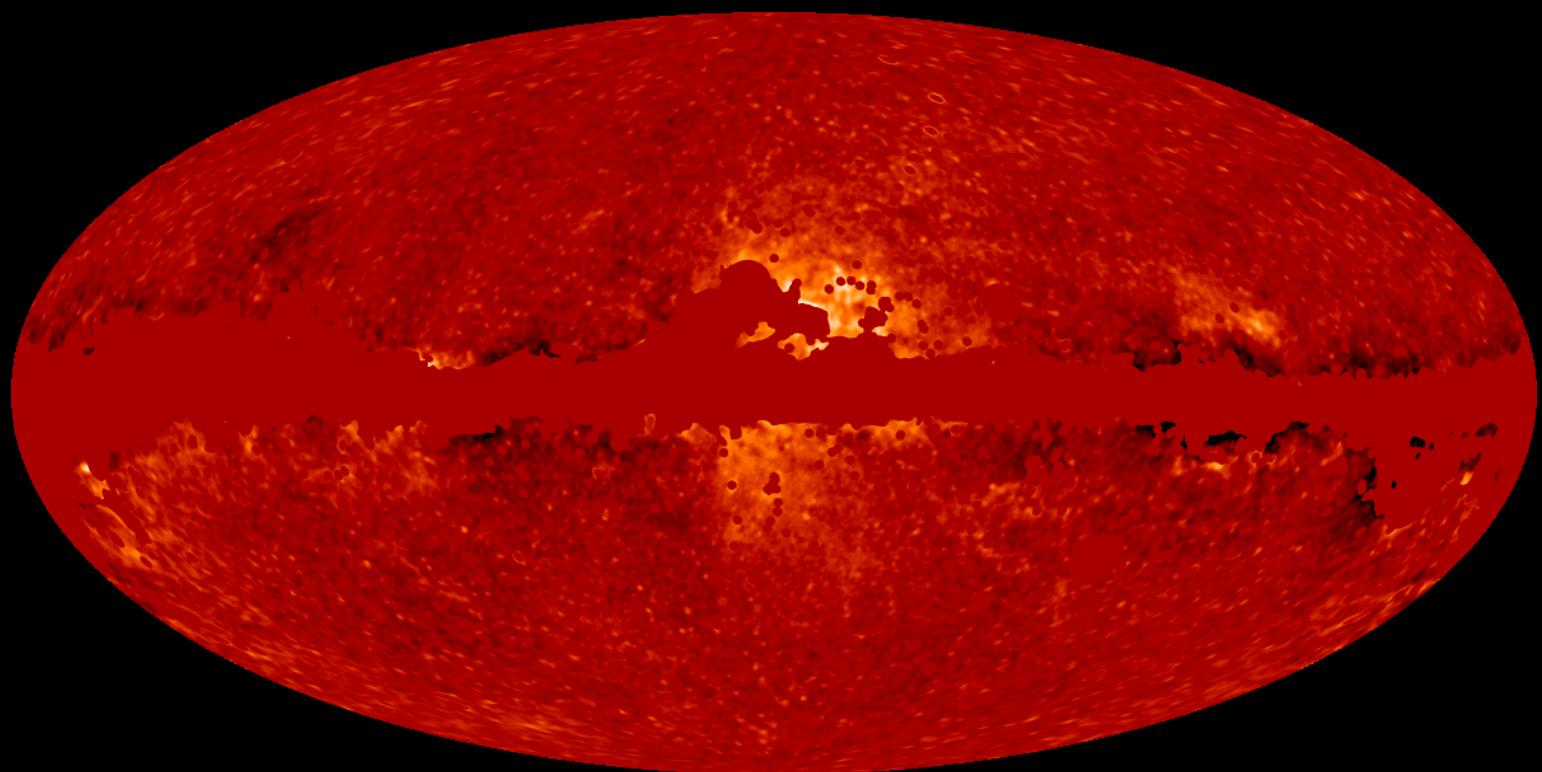
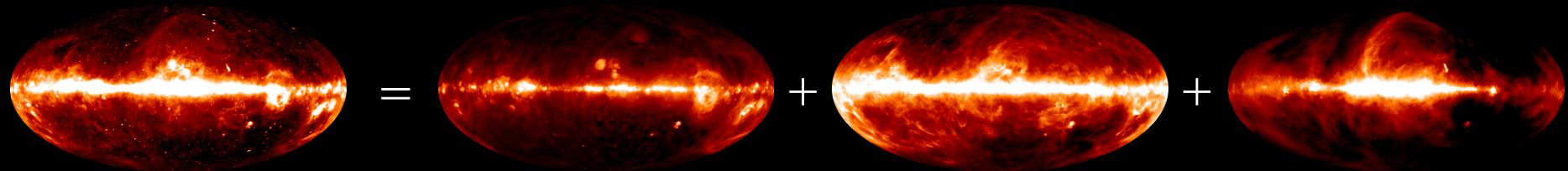
$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



WMAP 23 GHz

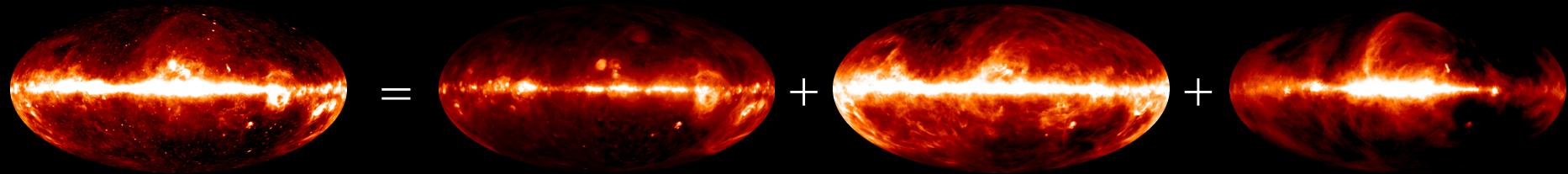
synchrotron $T_\nu \propto \nu^{-3.0}$

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

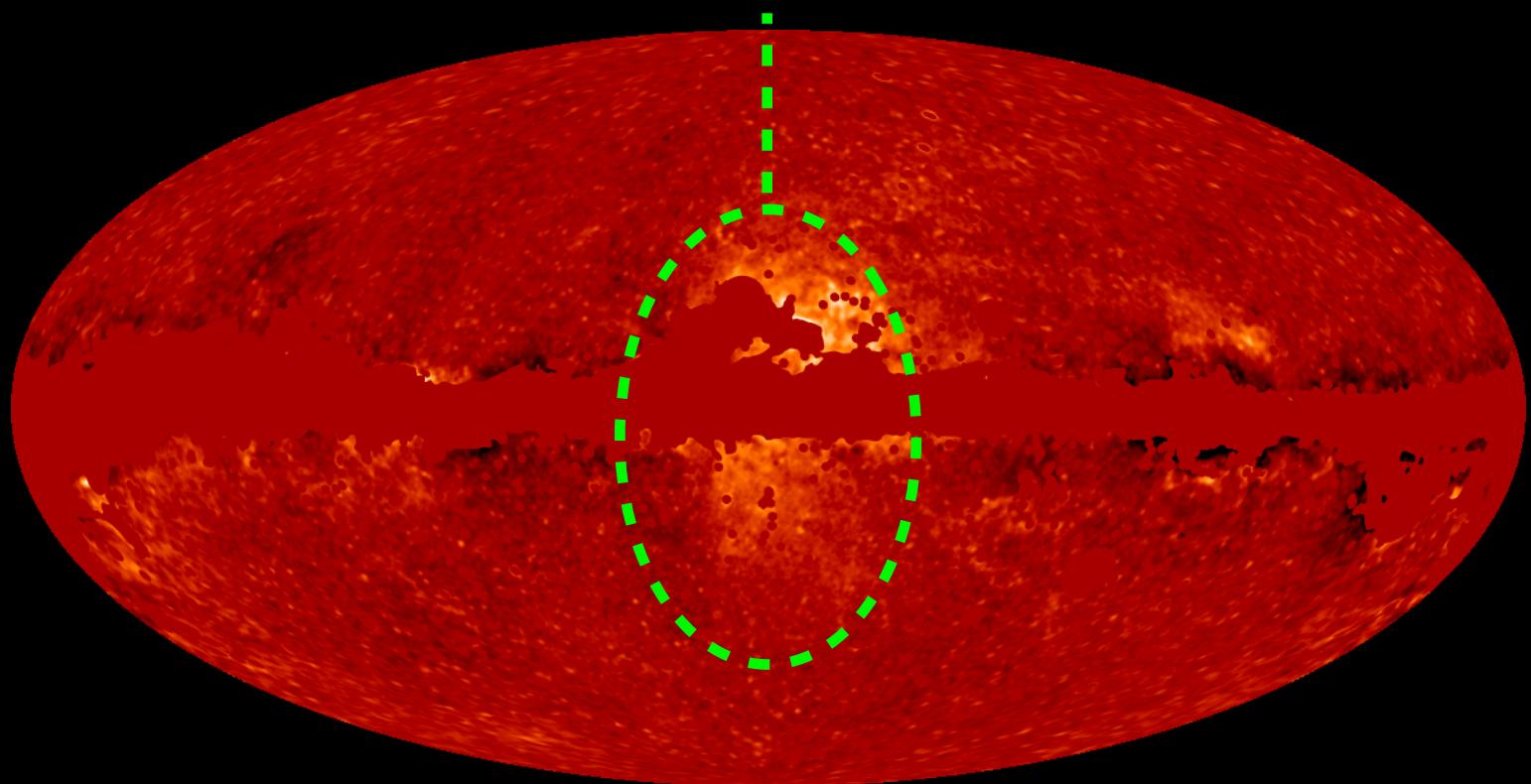


WMAP 23 GHz

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

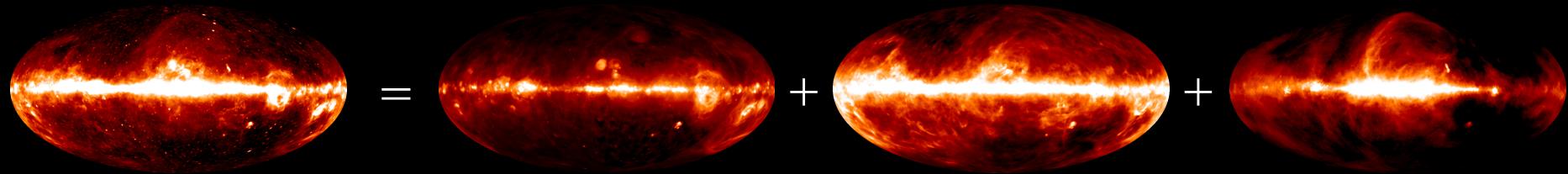


microwave “haze”

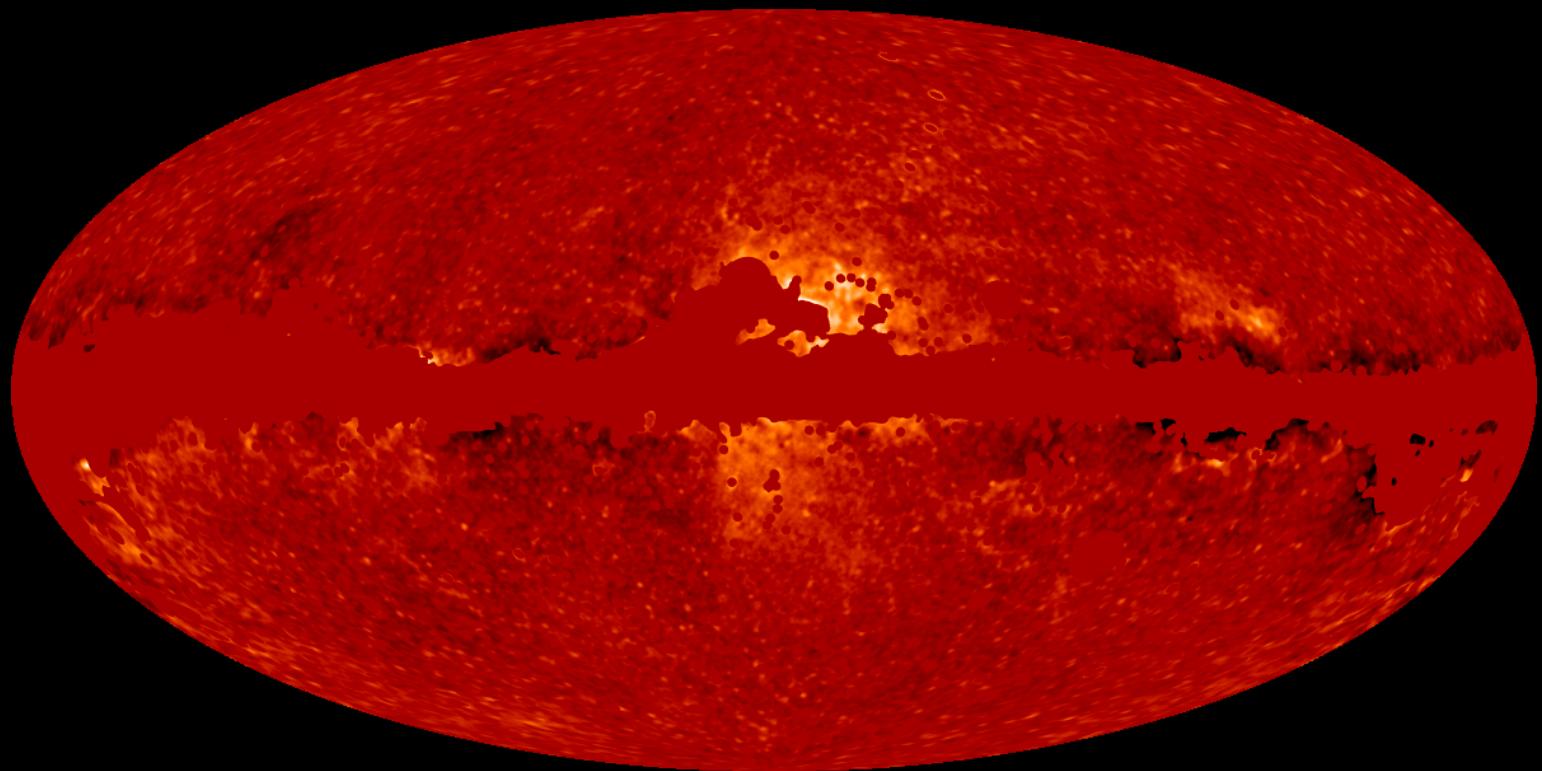


WMAP 23 GHz

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



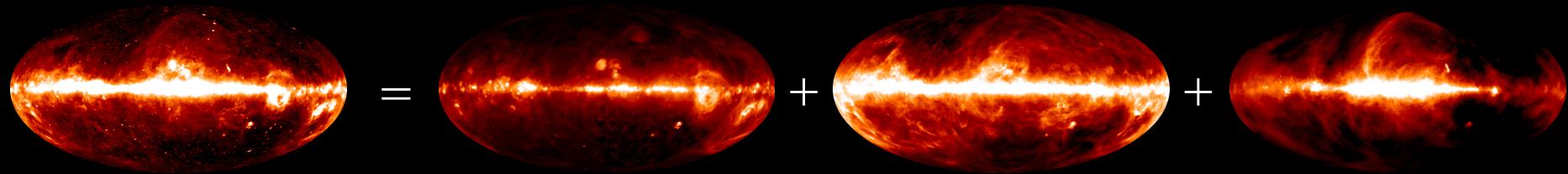
microwave haze



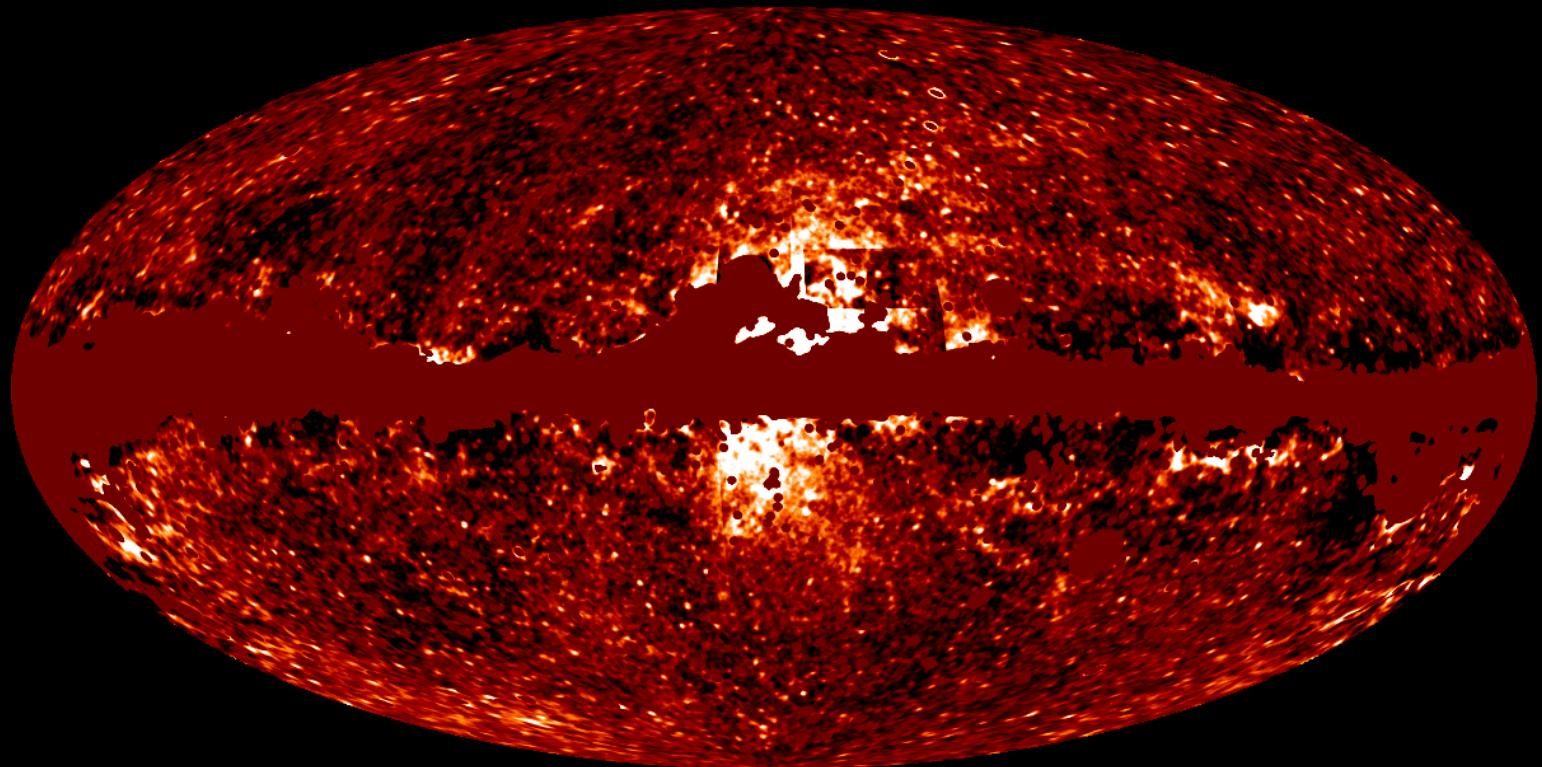
WMAP 23 GHz

“full sky fit”

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$



microwave haze

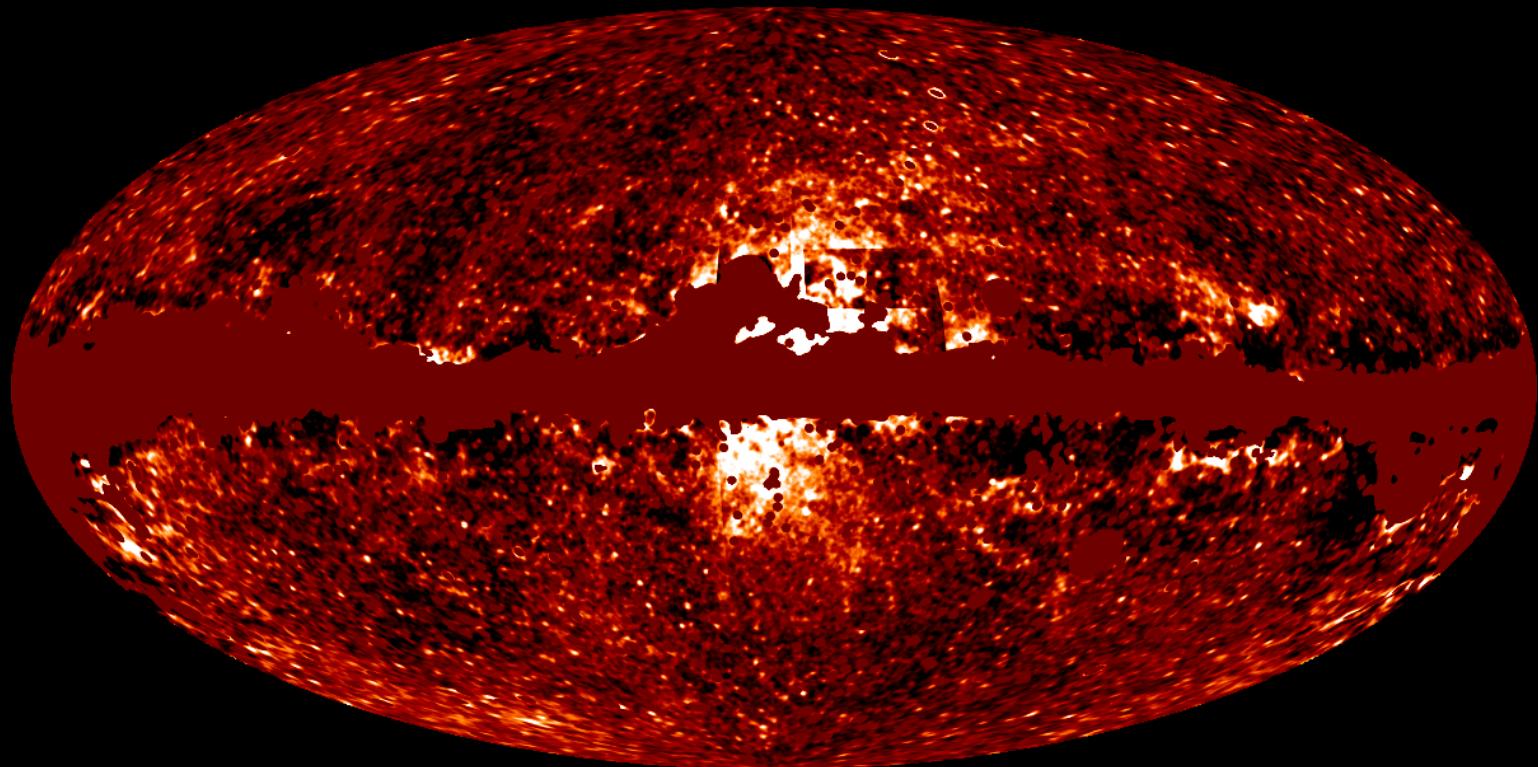


WMAP 23 GHz

“regional fit”

what is it? (we'll get to that) but first, what makes it unique?

microwave haze



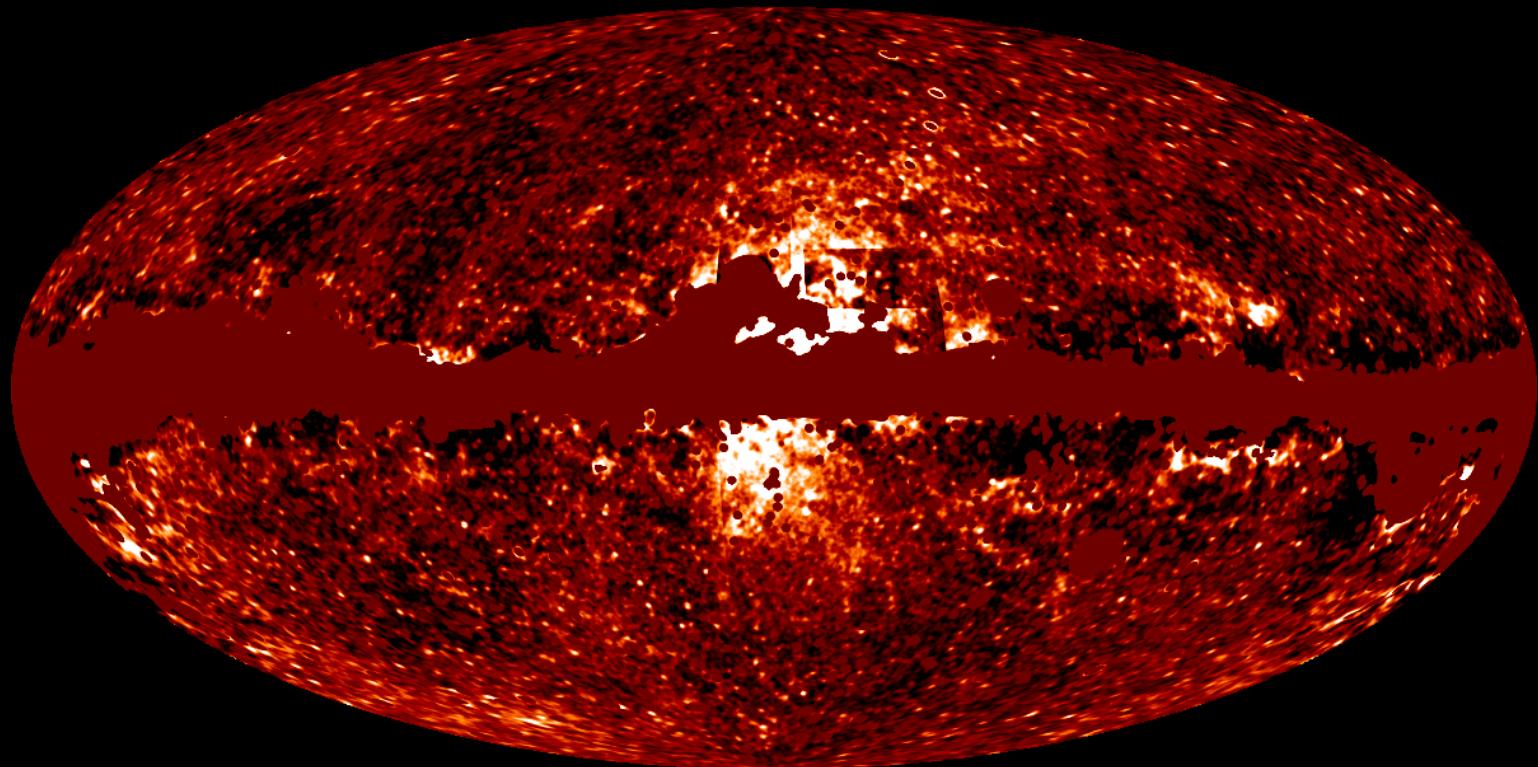
WMAP 23 GHz

Dobler (2012a)

what is it? (we'll get to that) but first, what makes it unique?

- . diffuse and extended ($\sim 5 \text{ kpc} \times 12 \text{ kpc}$)

microwave haze



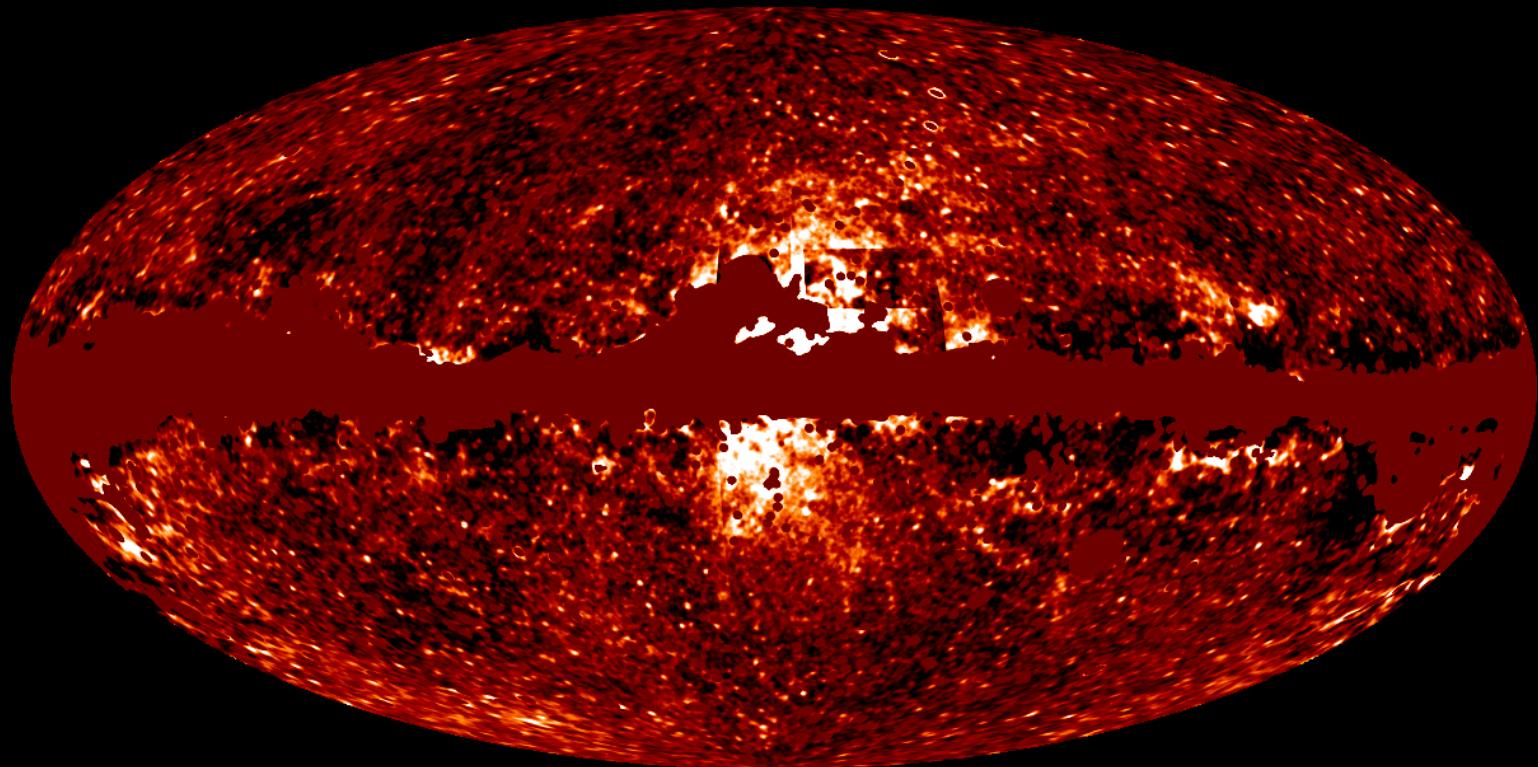
WMAP 23 GHz

Dobler (2012a)

what is it? (we'll get to that) but first, what makes it unique?

- . diffuse and extended ($\sim 5 \text{ kpc} \times 12 \text{ kpc}$)
- . spectrum

microwave haze

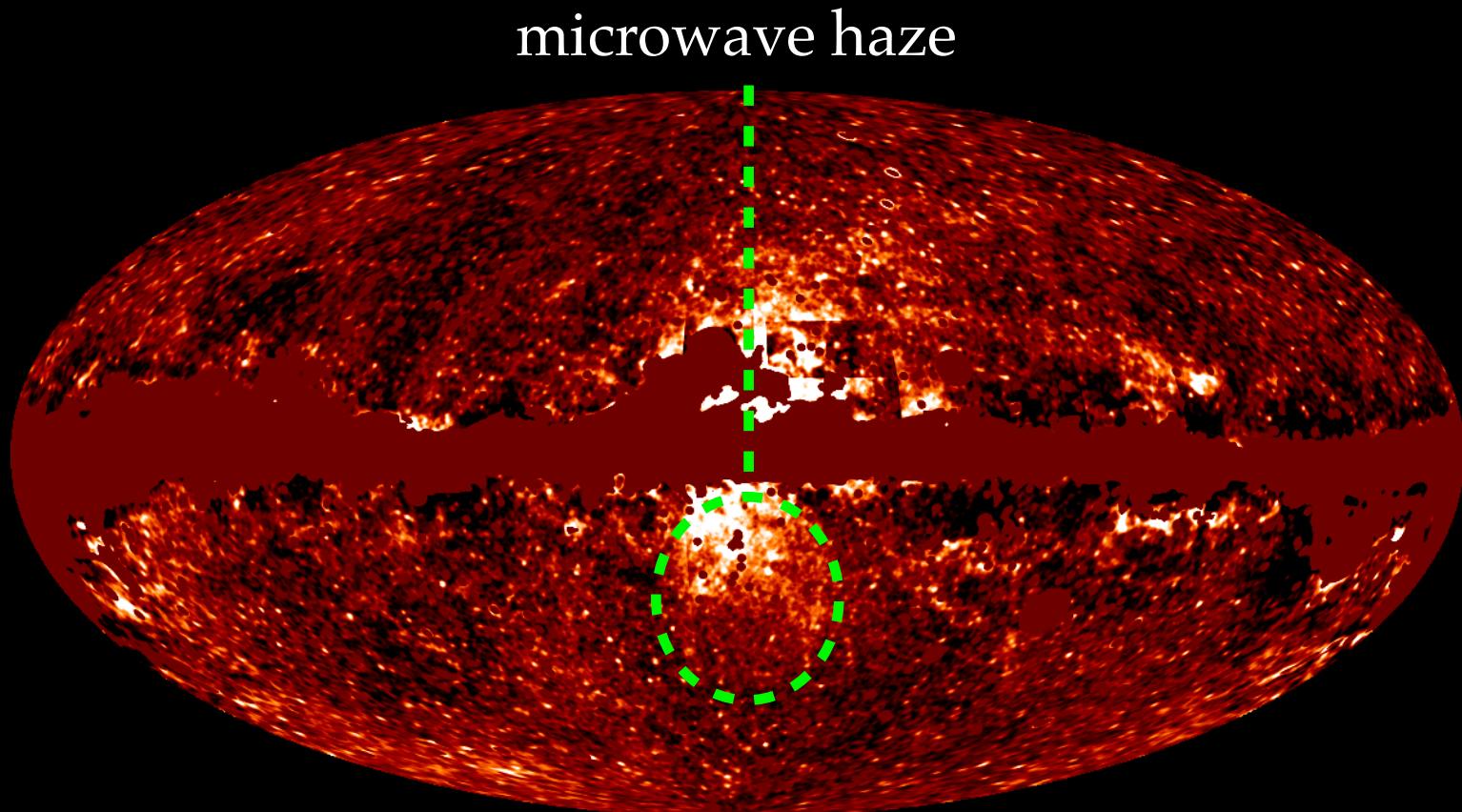


WMAP 23 GHz

Dobler (2012a)

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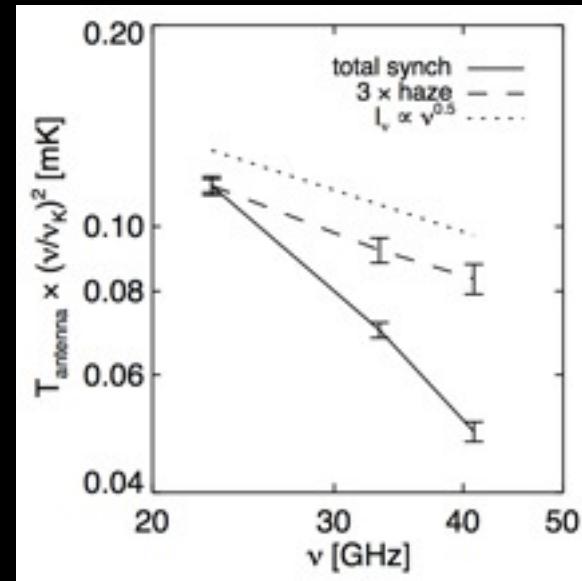
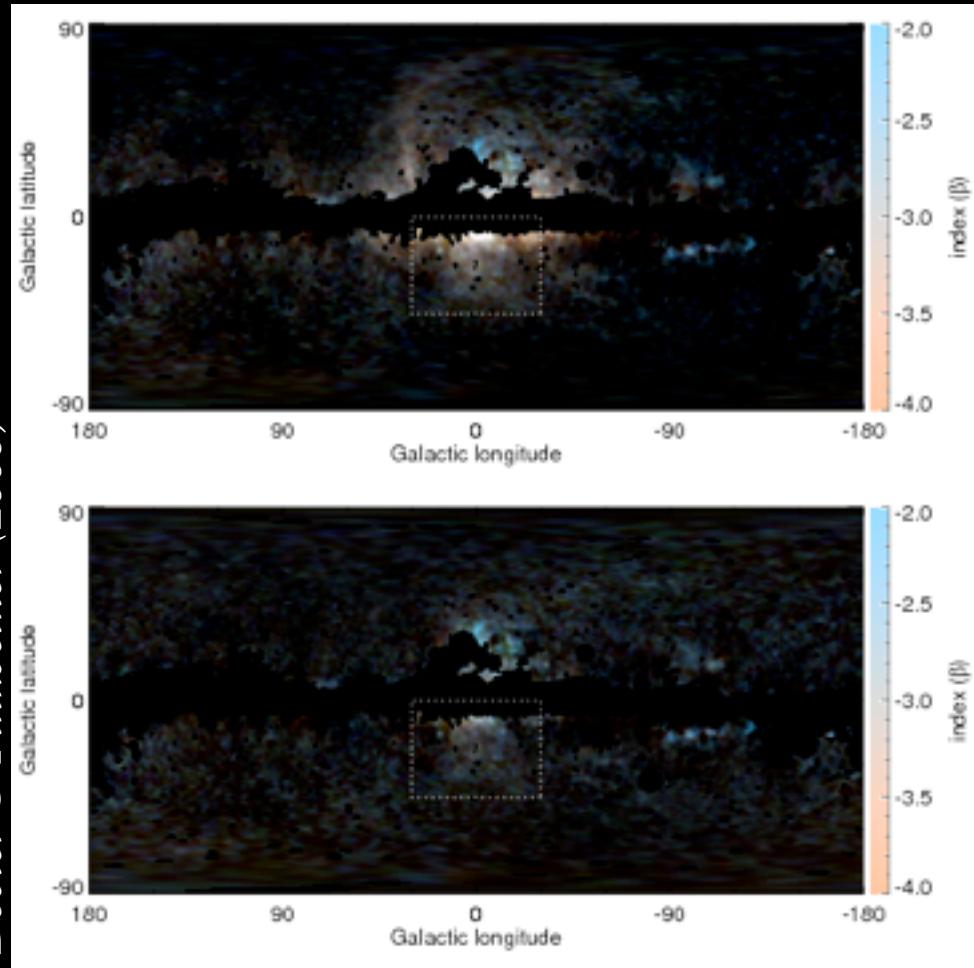


WMAP 23 GHz

Dobler (2012a)

what is it? (we'll get to that) but first, what makes it unique?

- . diffuse and extended ($\sim 5 \text{ kpc} \times 12 \text{ kpc}$)
- . spectrum



consistent with synchrotron
from a *very hard* electron
population:

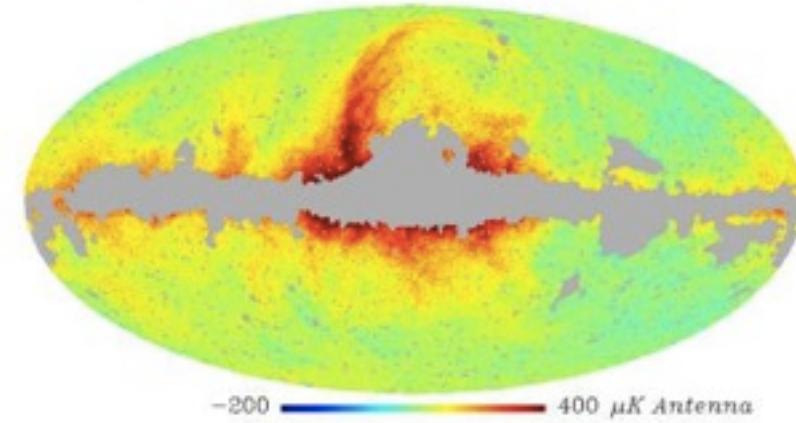
$$dN/dE \propto E^{-2.0}$$

bayesian (Gibbs) WMAP+Haslam pixel based model:

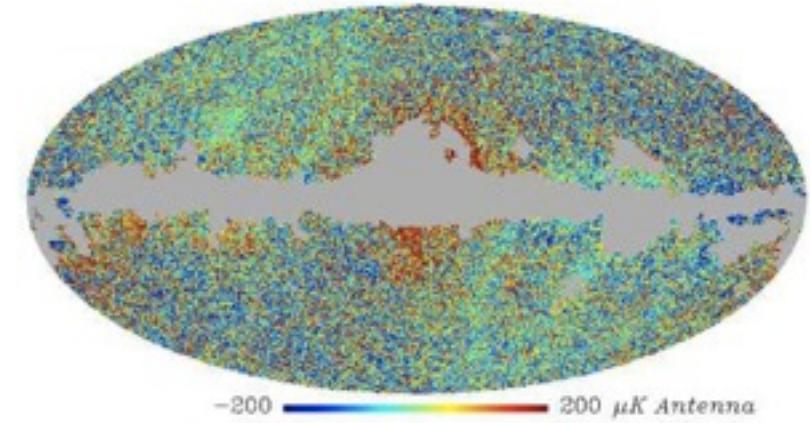
- . free-free component $\propto \nu^{-2.15}$
- . low frequency soft synchrotron component $\propto \nu^{-3.0}$
- . low frequency power law $\propto \nu^\beta$
- . empirical thermal plus spinning dust spectrum
- . C_l sampled CMB

Pietrobon et al. (2012)

Synchrotron @ 23 GHz: Haslam+WMAP7



Residual Low-freq. Comp. @ 23 GHz: Haslam+WMAP7

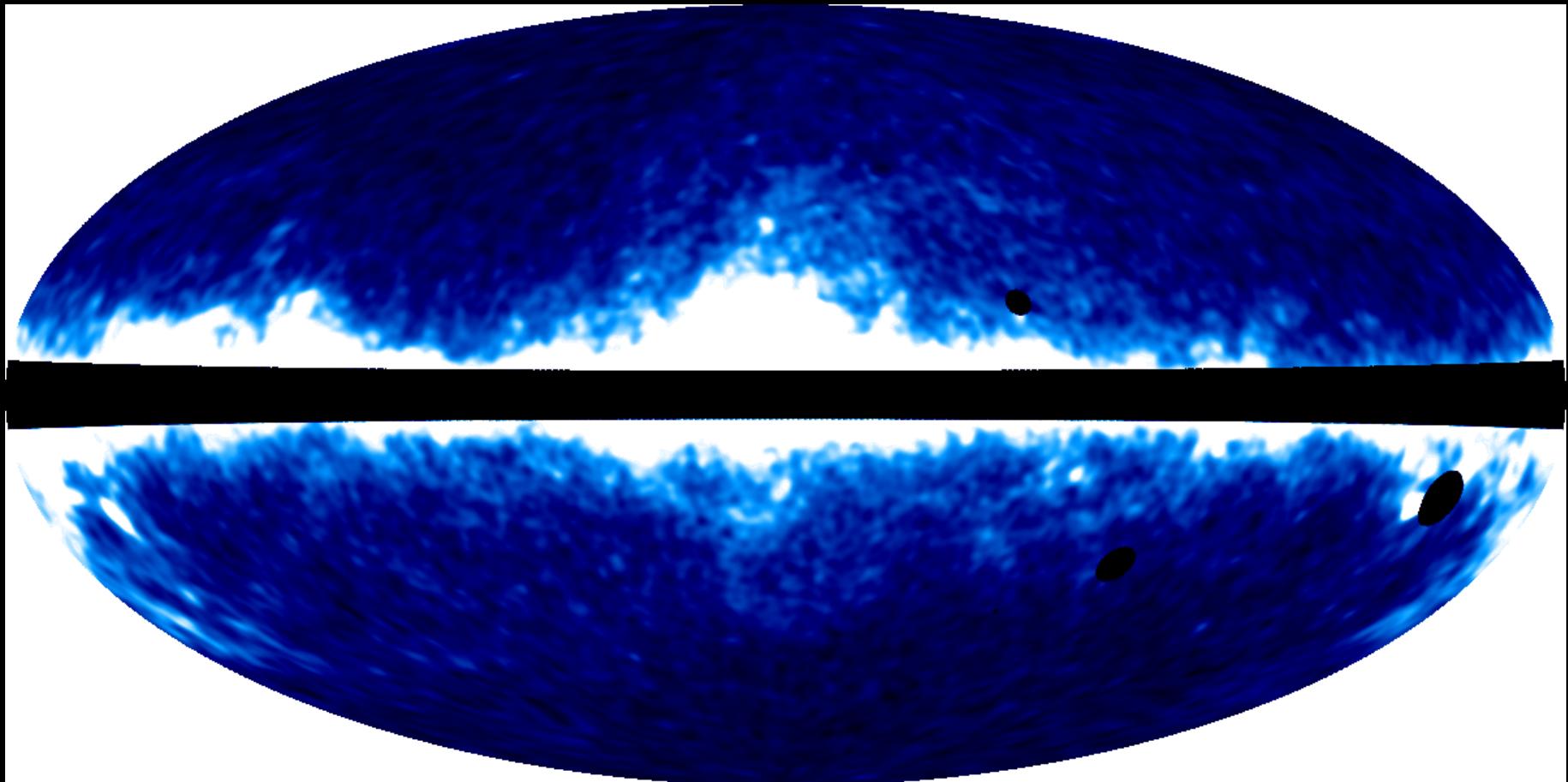


soft synchrotron component is highly correlated with Haslam: i.e., synchrotron index is ~ 3.0 everywhere except the haze region => **separate component**

gamma-rays...

gamma-rays...

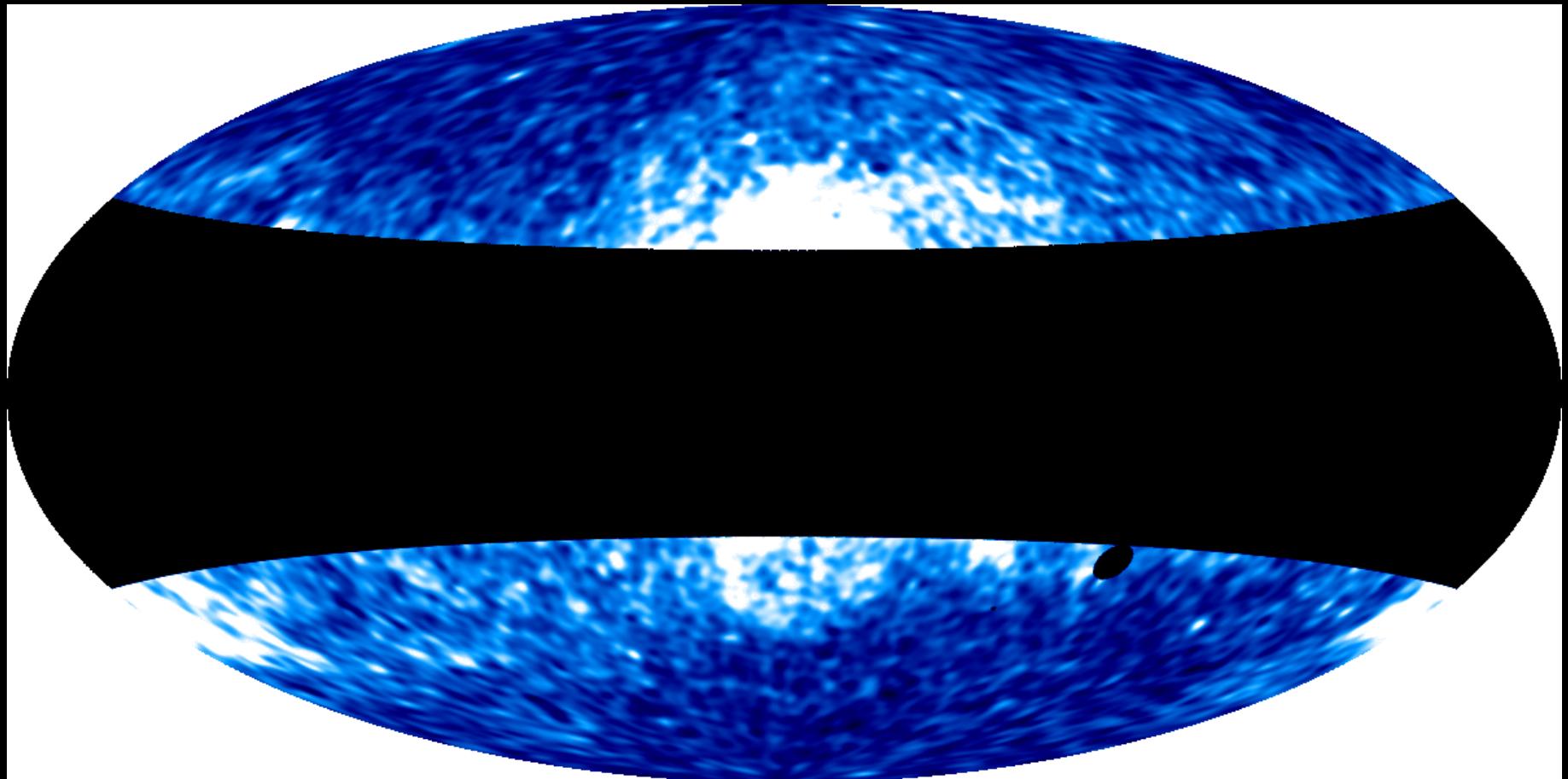
Dobler et al. (2010)



Fermi 2-5 GeV

gamma-rays...

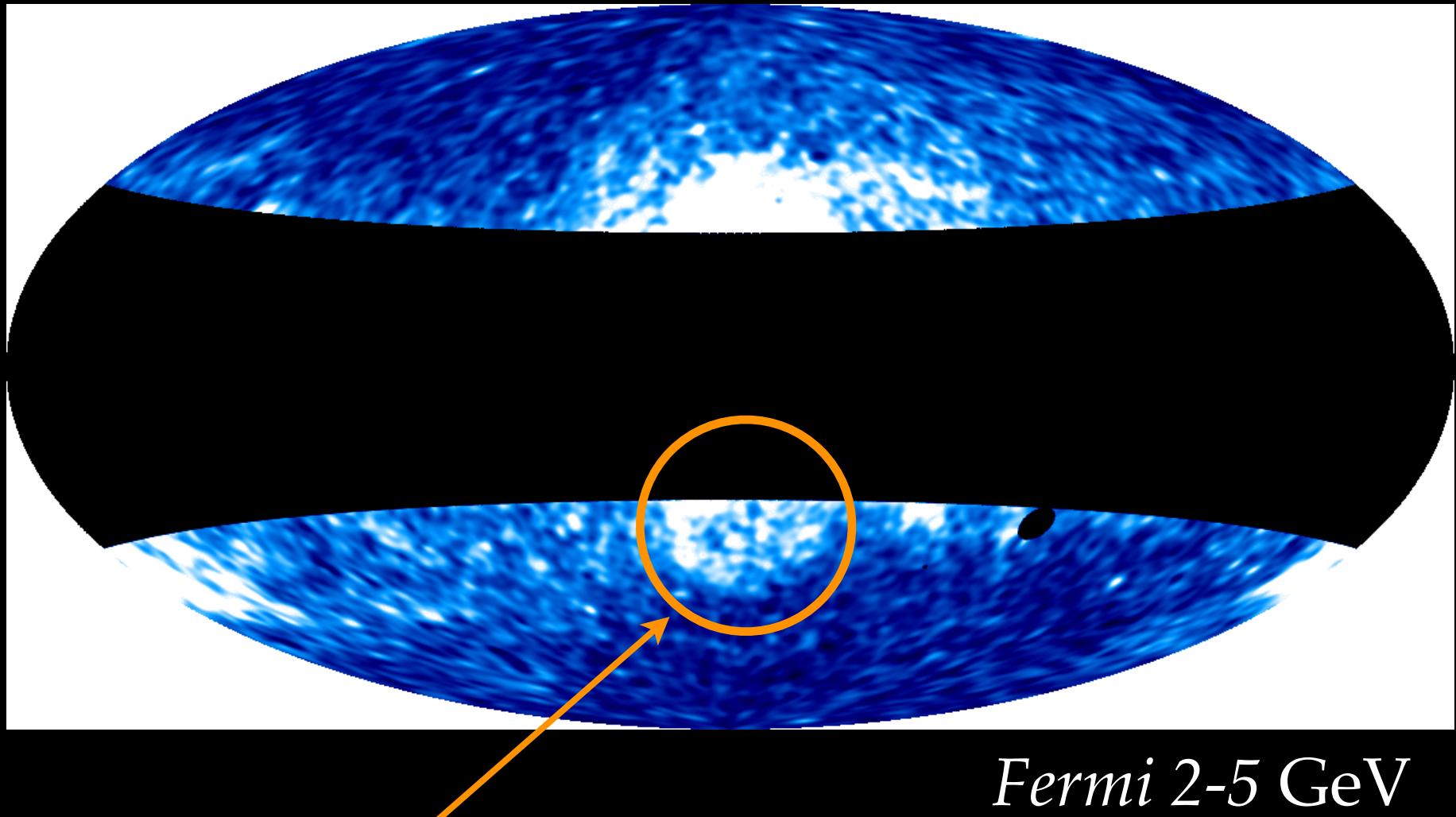
Dobler et al. (2010)



Fermi 2-5 GeV

gamma-rays...

Dobler et al. (2010)

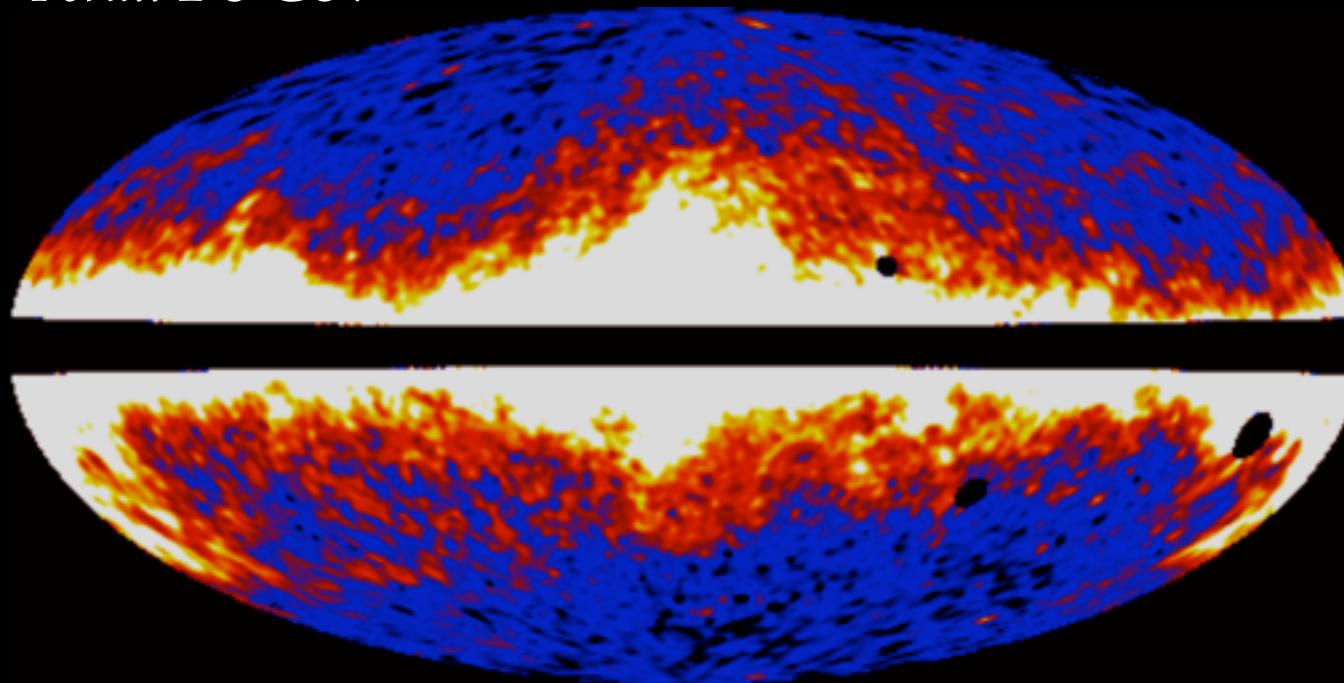


Fermi 2-5 GeV

visible *even* with *no* templates, *no* fitting, *no* subtraction, etc...

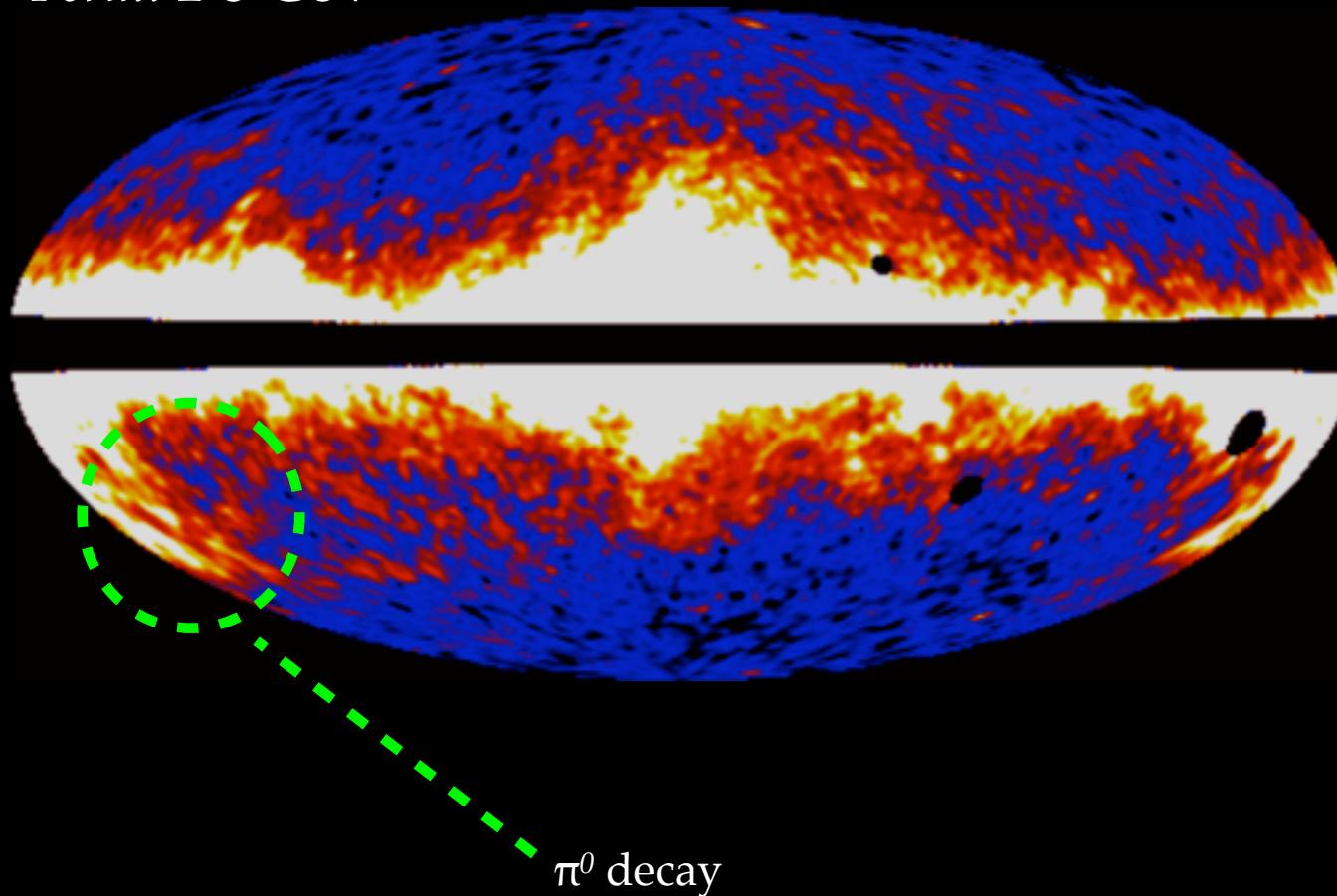
gamma-rays from the Galaxy

Fermi 2-5 GeV



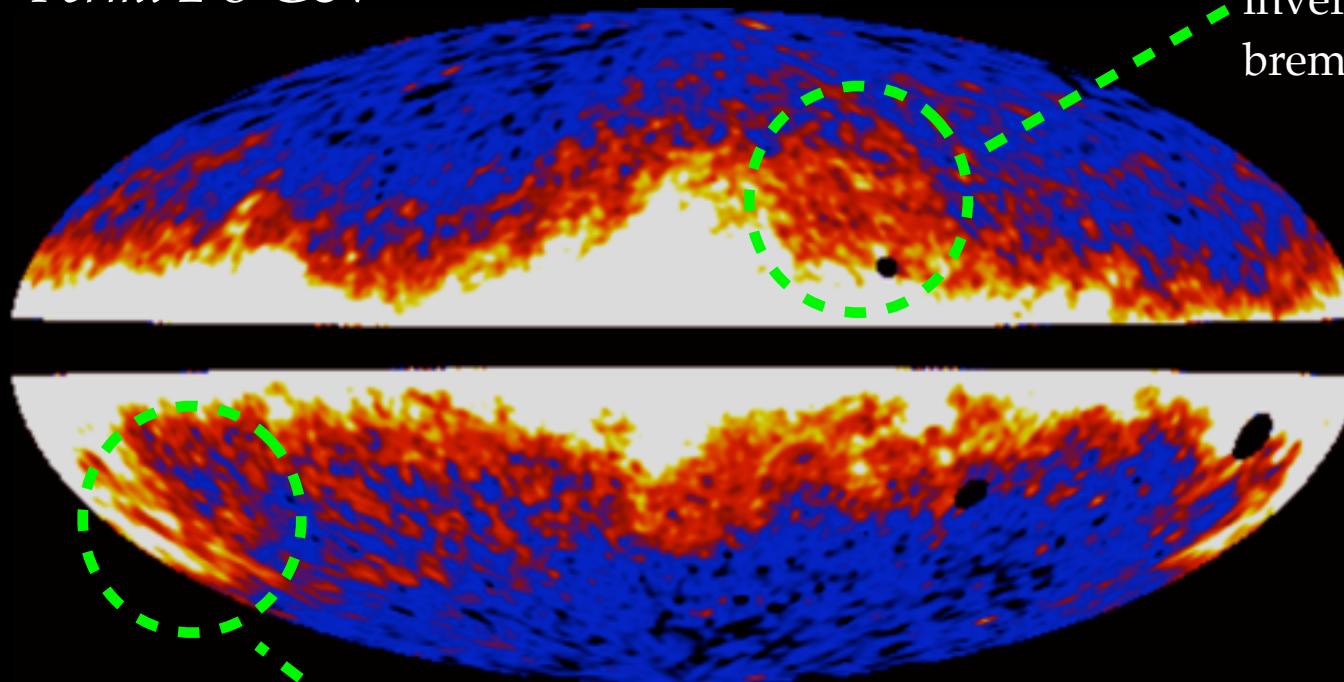
gamma-rays from the Galaxy

Fermi 2-5 GeV



gamma-rays from the Galaxy

Fermi 2-5 GeV

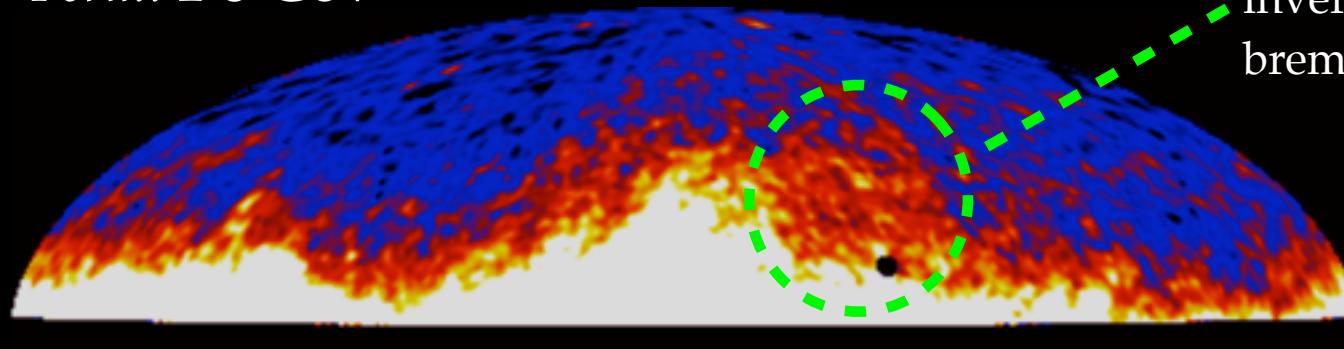


inverse Compton plus
bremsstrahlung (subdominant)

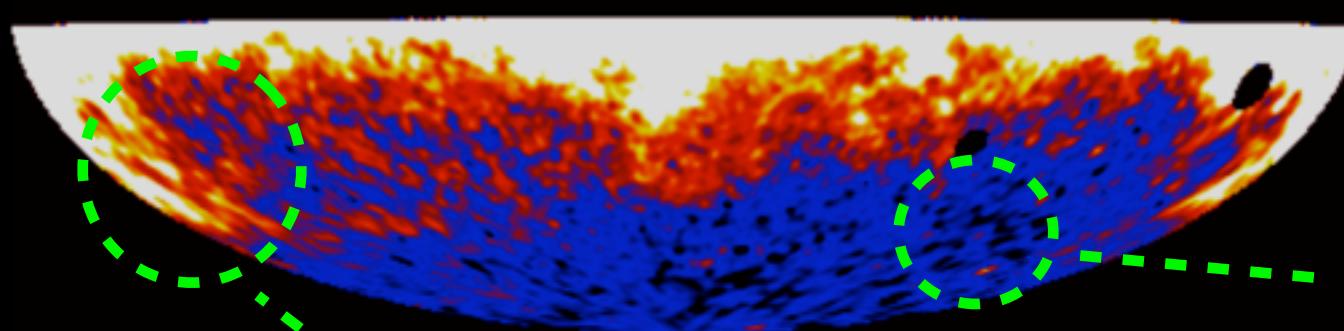
π^0 decay

gamma-rays from the Galaxy

Fermi 2-5 GeV



inverse Compton plus
bremsstrahlung (subdominant)

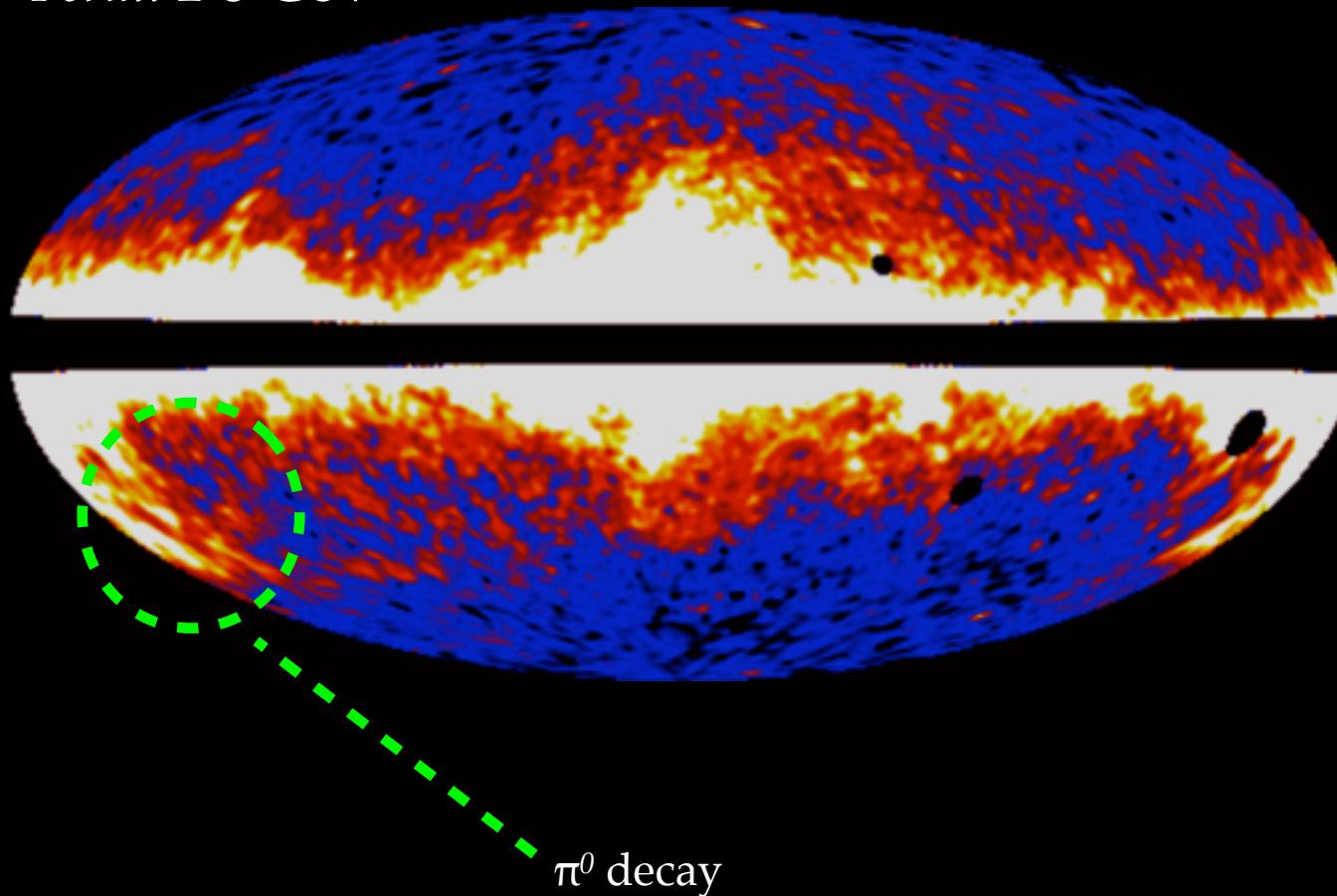


extragalactic plus
particle contamination

π^0 decay

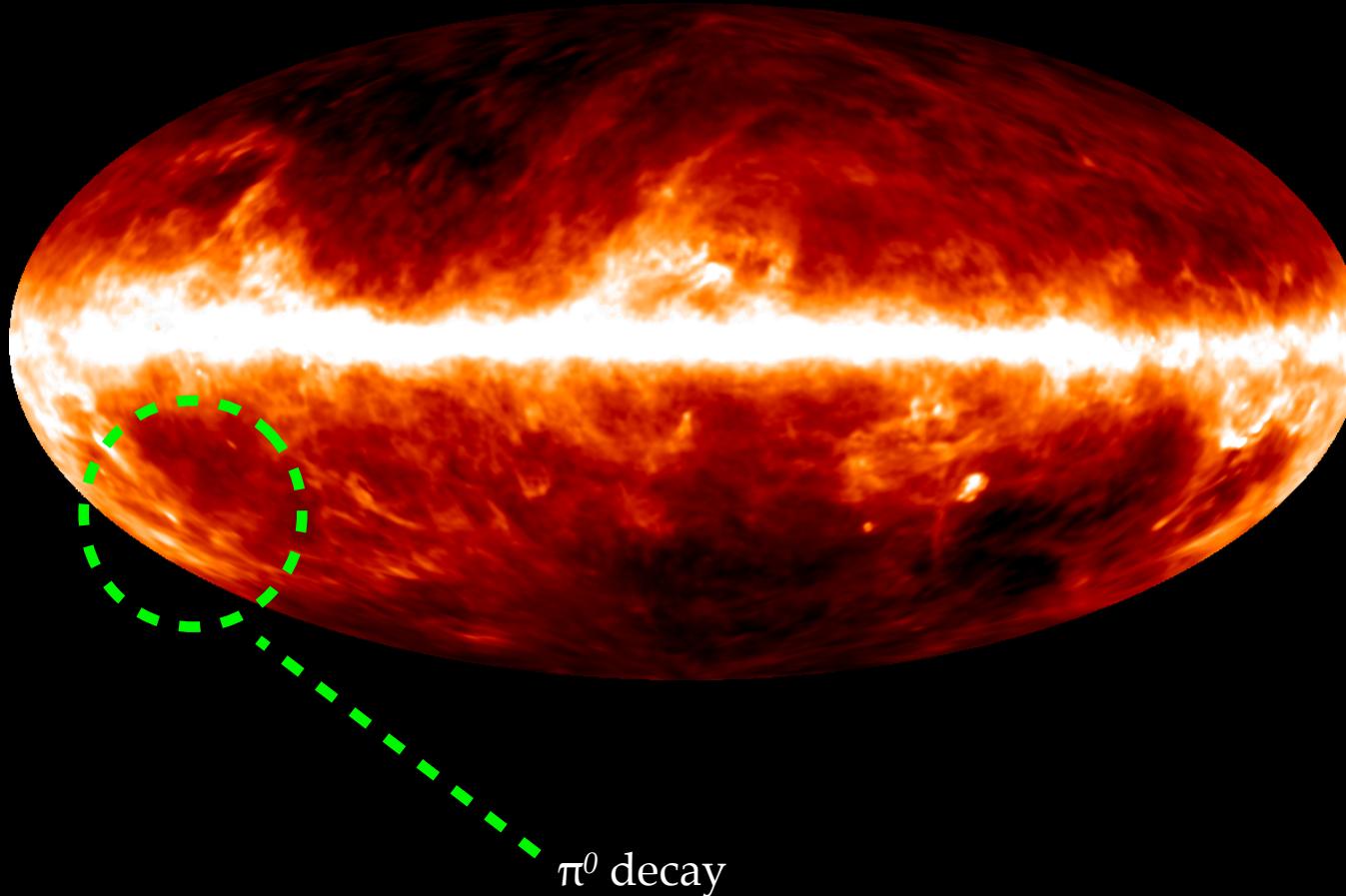
gamma-rays from the Galaxy

Fermi 2-5 GeV



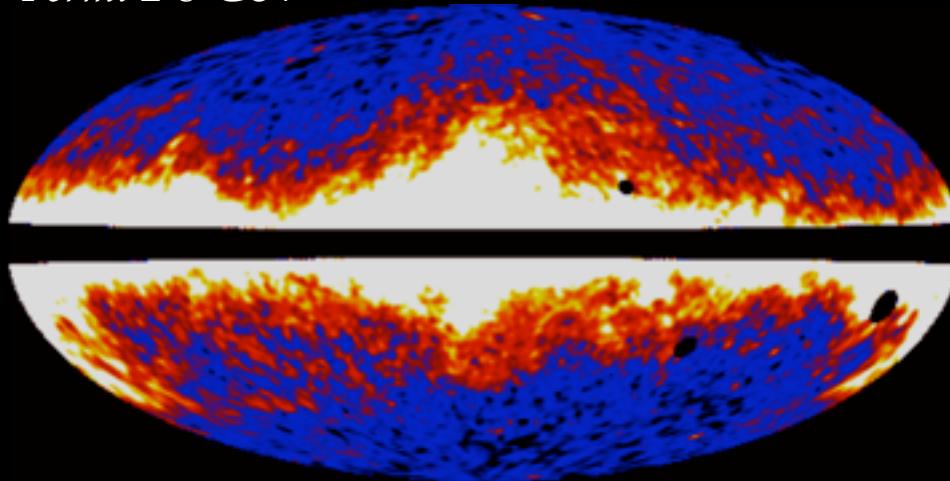
morphological tracers of emission

Schlegel, Finkbeiner, & Davis (1998)

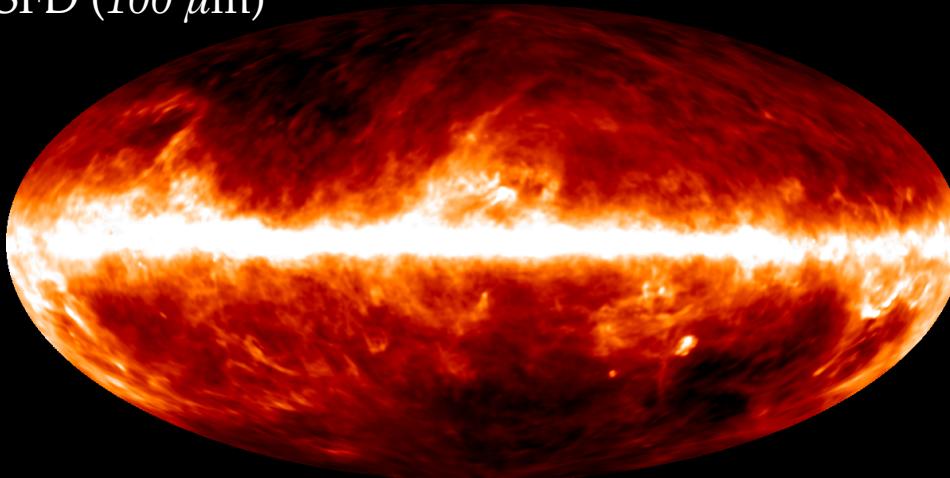


morphological tracers of emission

Fermi 2-5 GeV

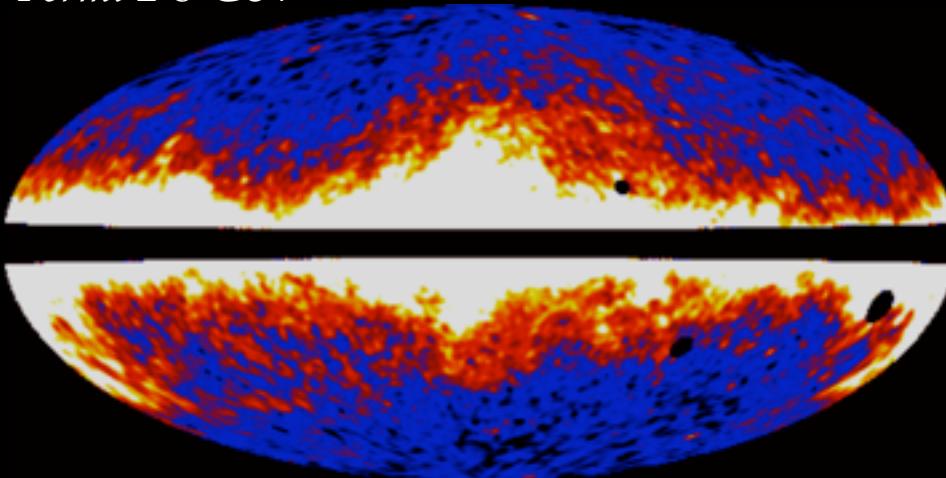


SFD ($100 \mu\text{m}$)

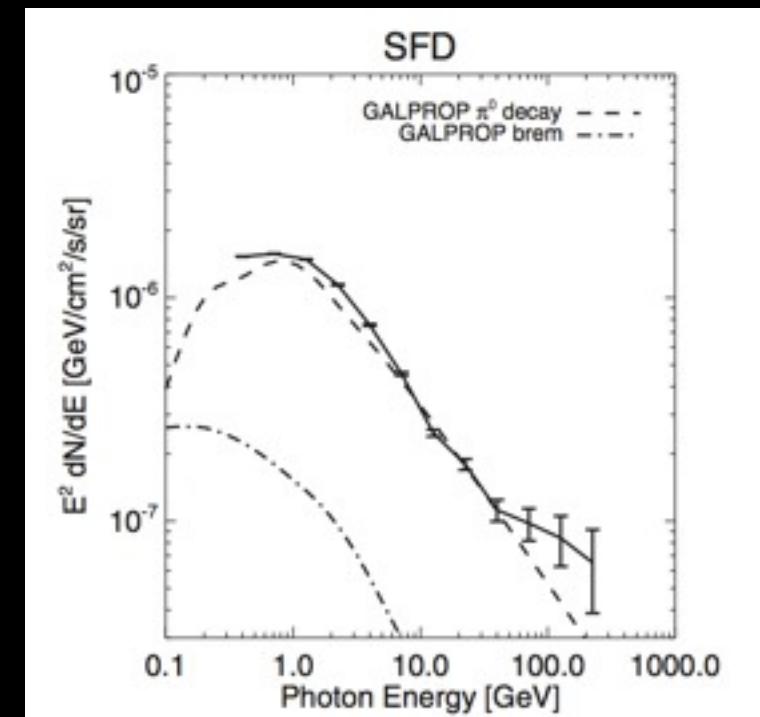
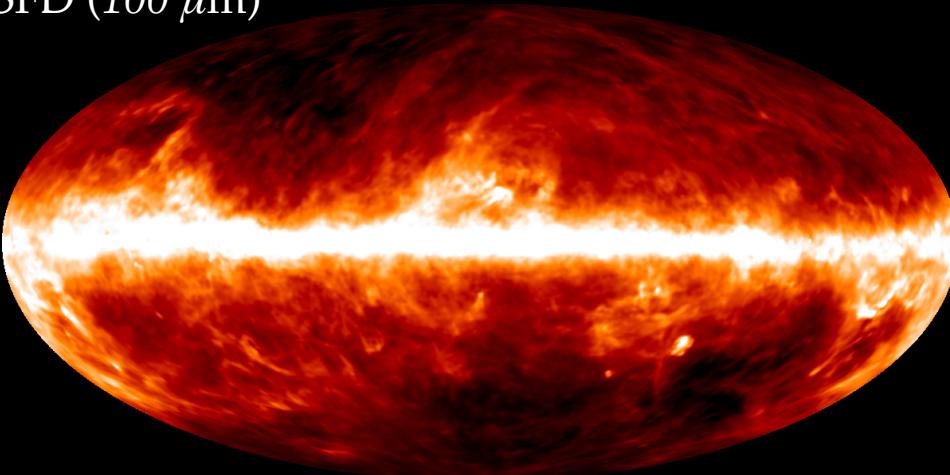


morphological tracers of emission

Fermi 2-5 GeV

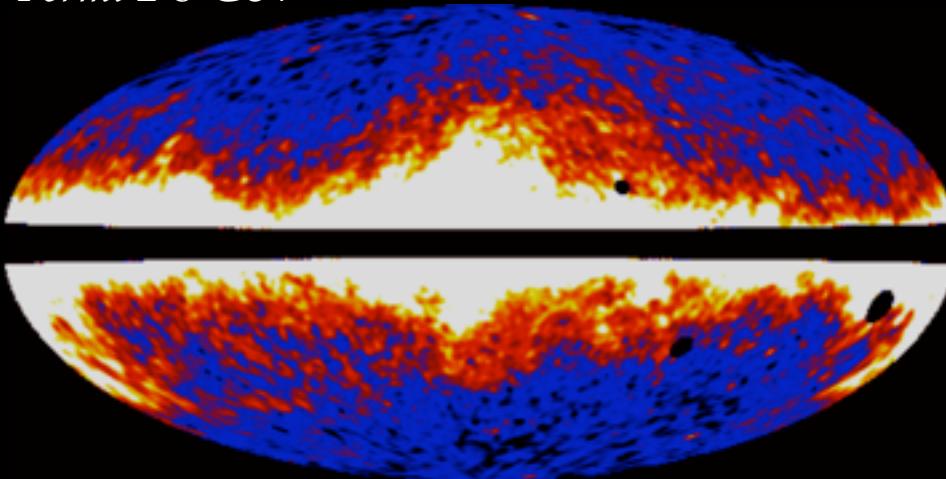


SFD (100 μm)

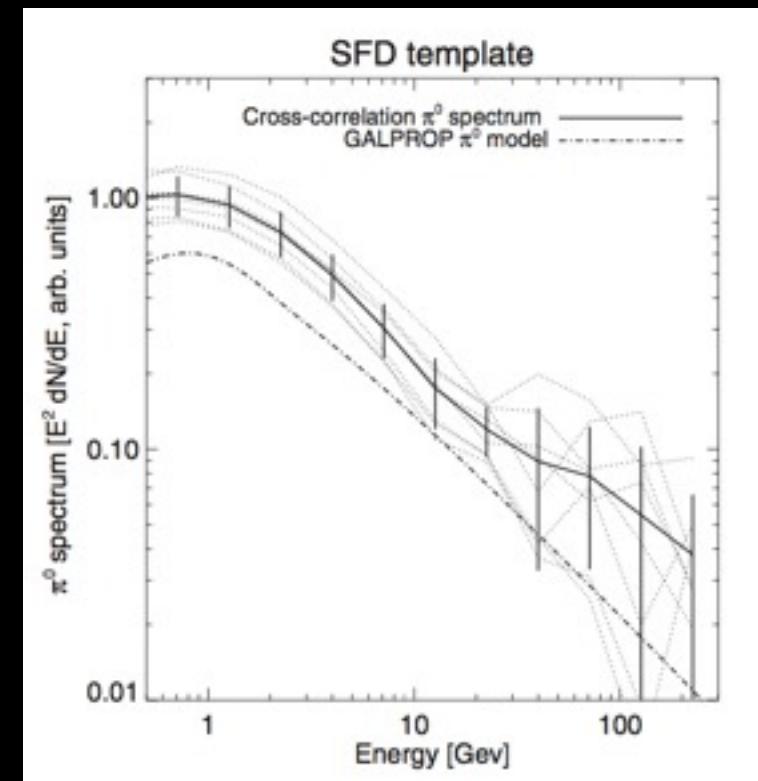
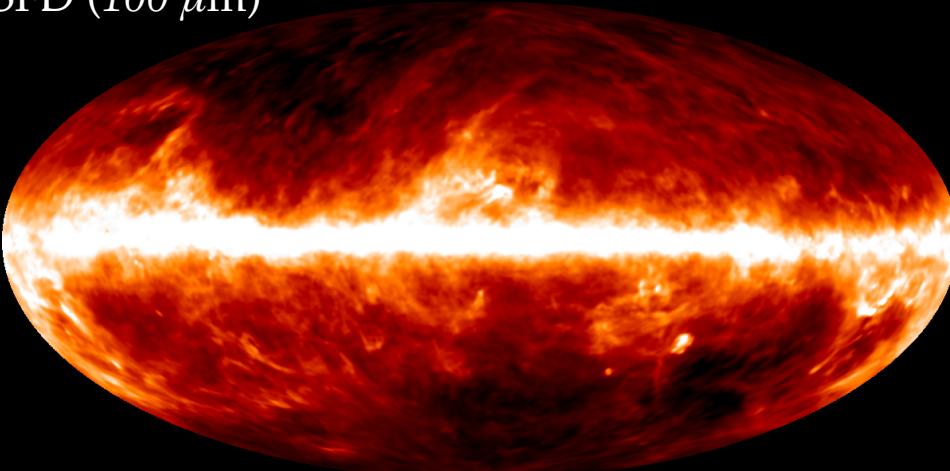
Dobler *et al.* (2010)

morphological tracers of emission

Fermi 2-5 GeV



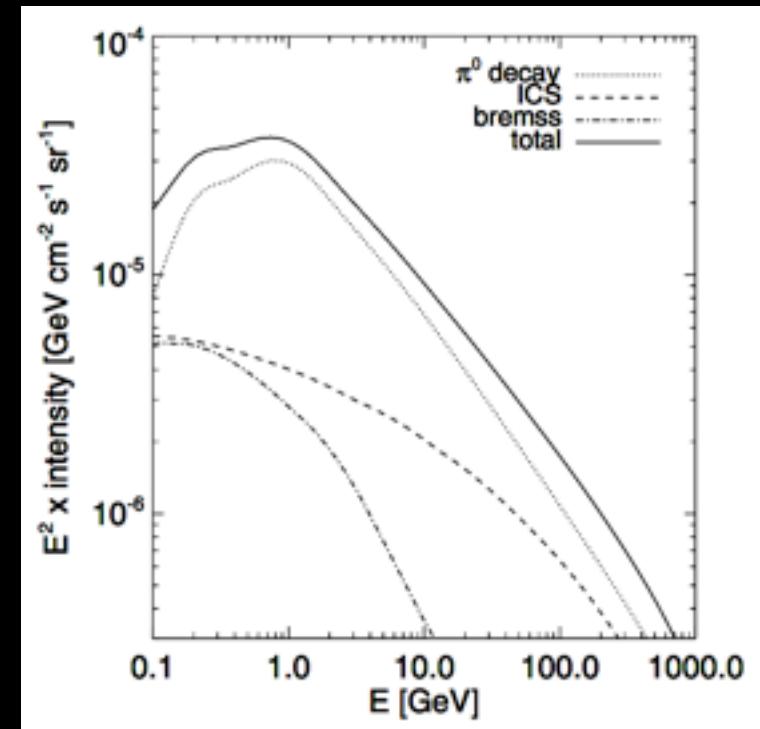
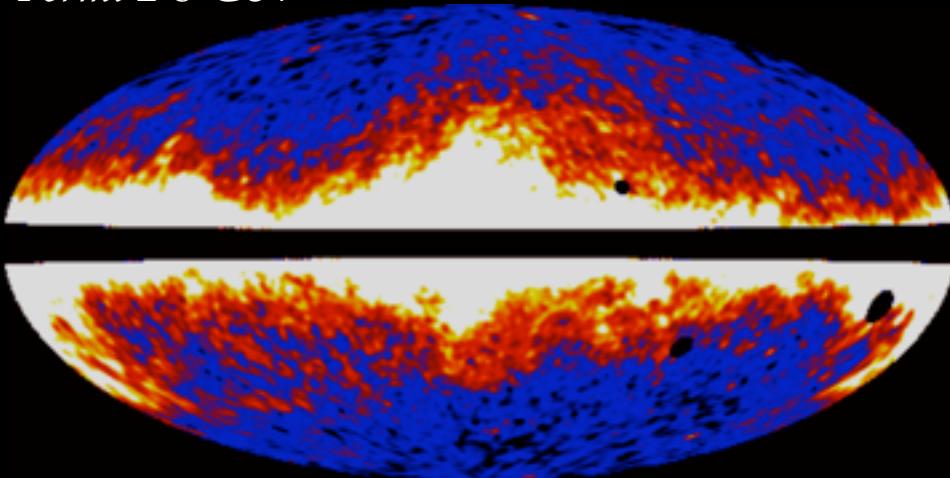
SFD ($100 \mu\text{m}$)



Dobler et al. (2010)

morphological tracers of emission

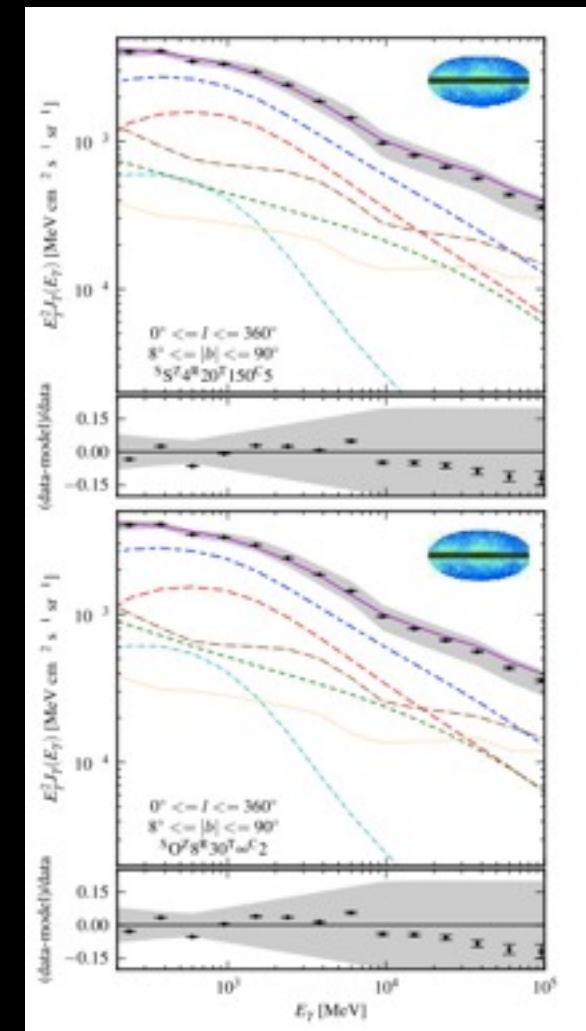
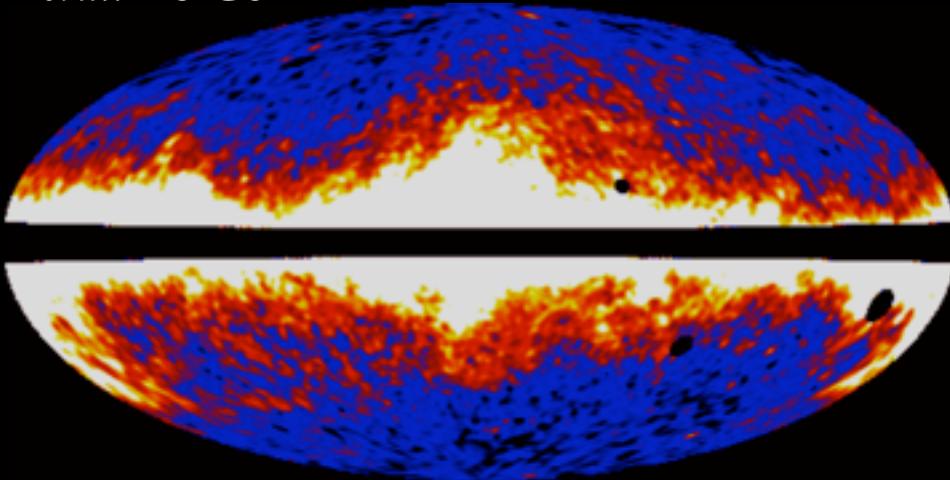
Fermi 2-5 GeV



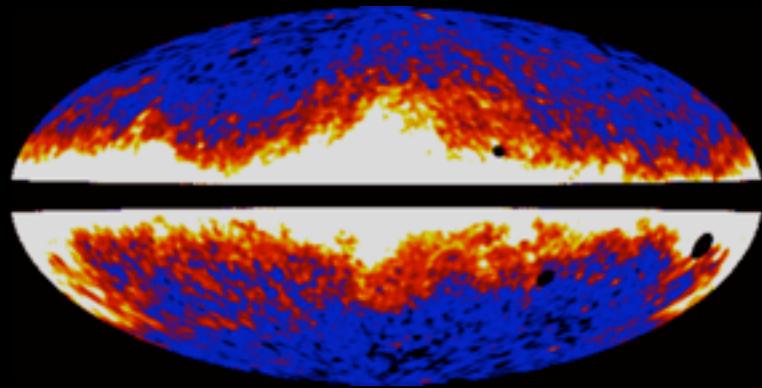
Dobler et al. (2010)

morphological tracers of emission

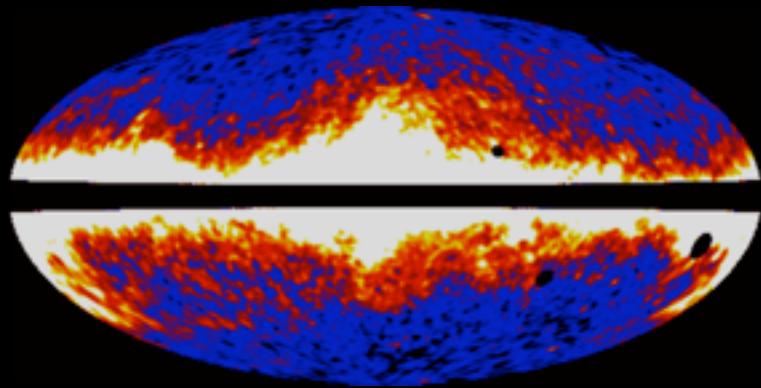
Fermi 2-5 GeV



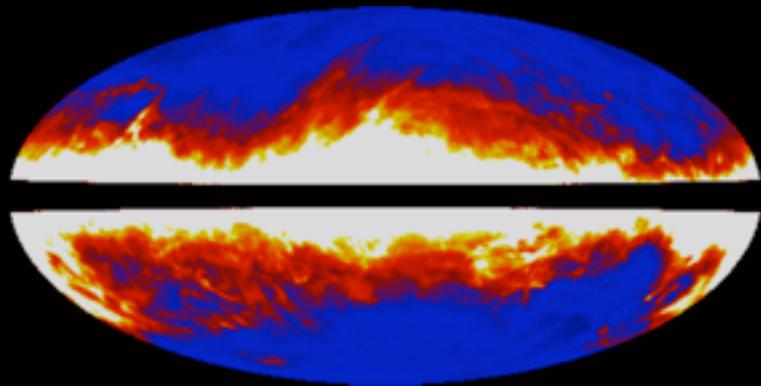
Fermi collab. (2012)



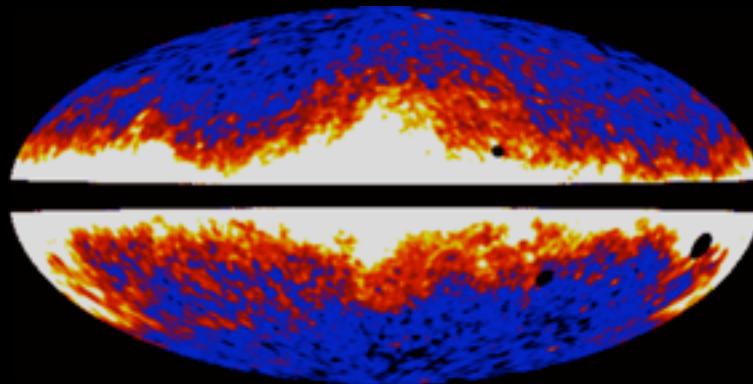
Fermi data 2-5 GeV



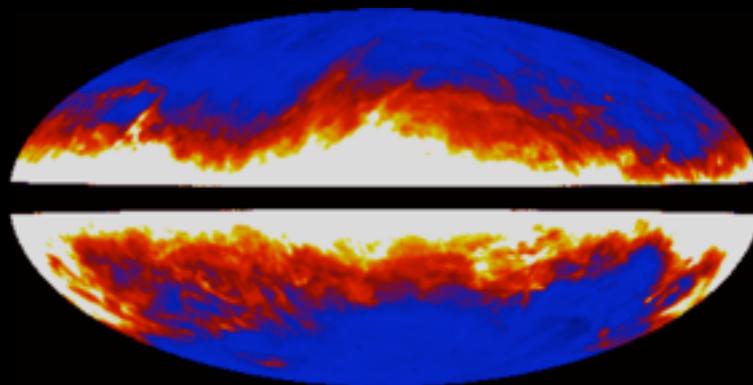
diffuse model 2-5 GeV



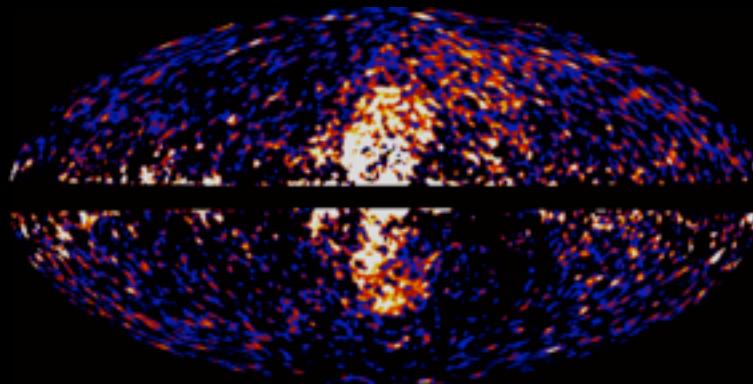
Fermi data 2-5 GeV

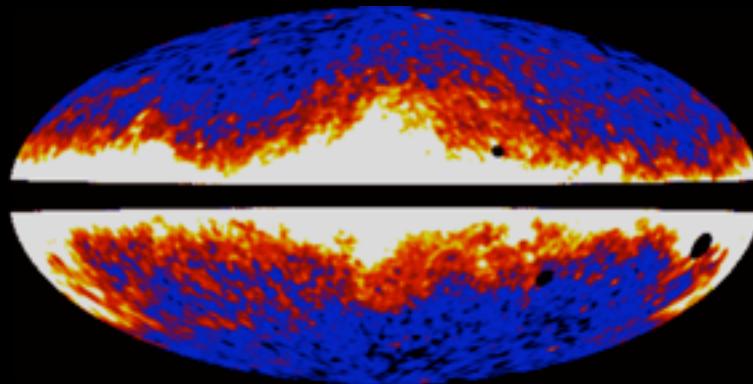


diffuse model 2-5 GeV

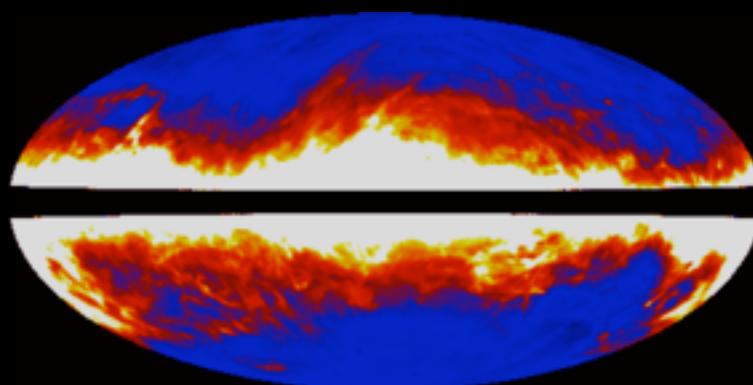
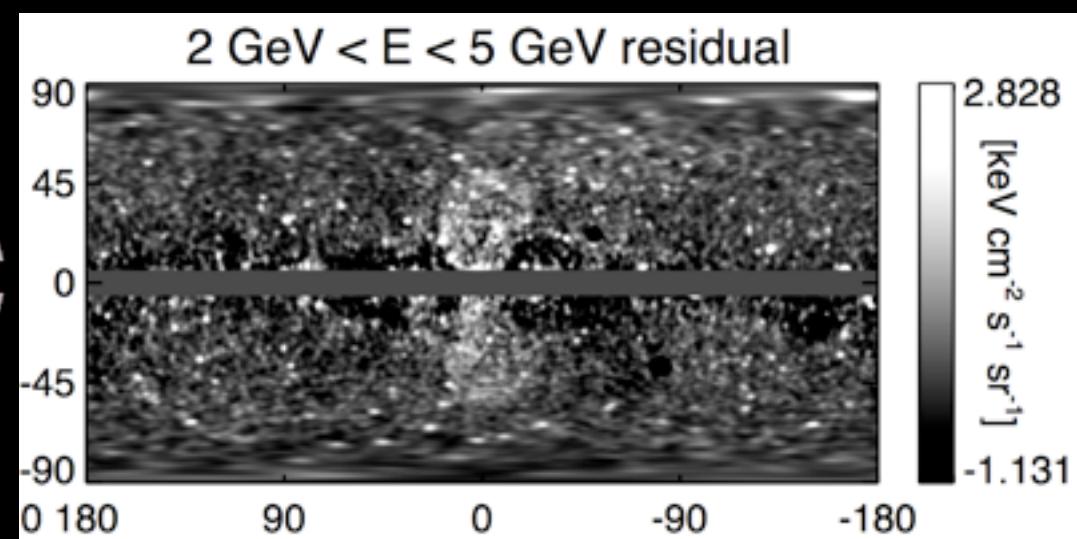
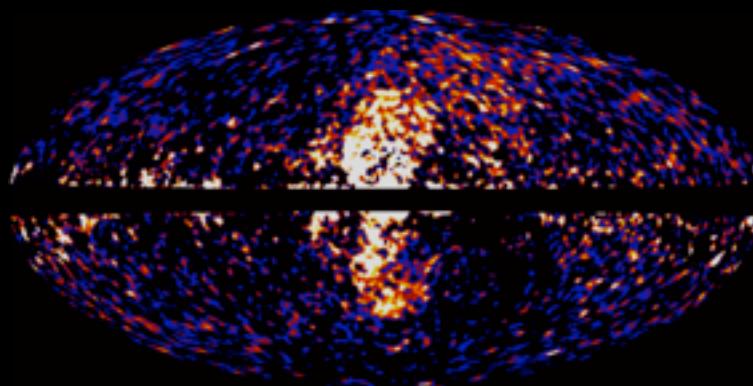


Fermi "haze/bubbles"

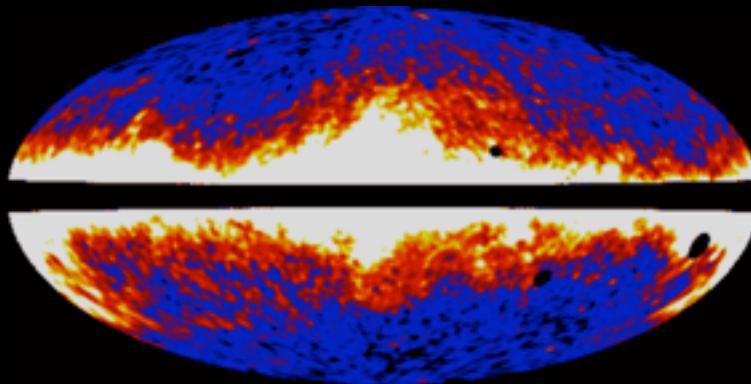


Fermi data 2-5 GeV

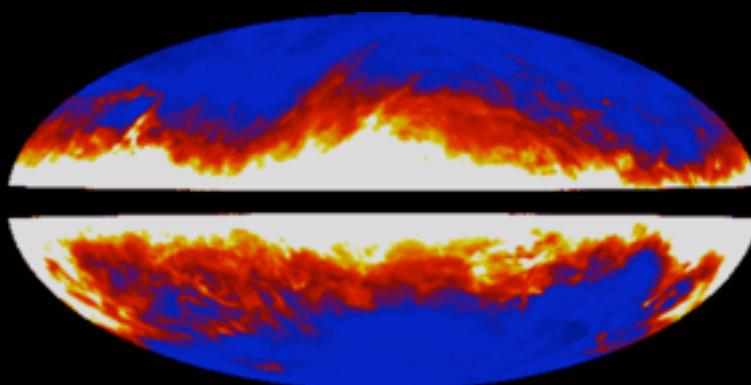
diffuse model 2-5 GeV

*Fermi* "haze/bubbles"*Fermi* "haze"

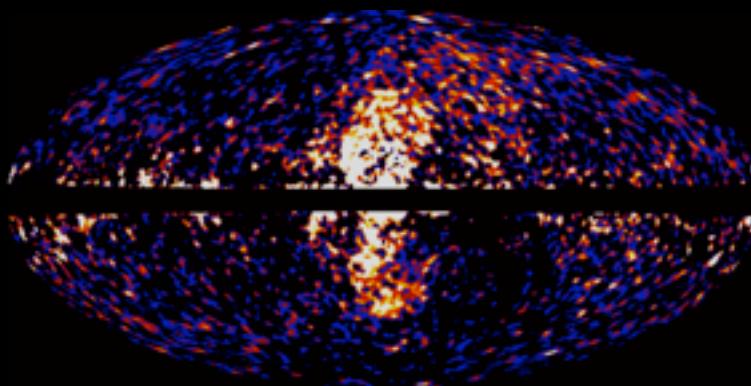
Fermi data 2-5 GeV



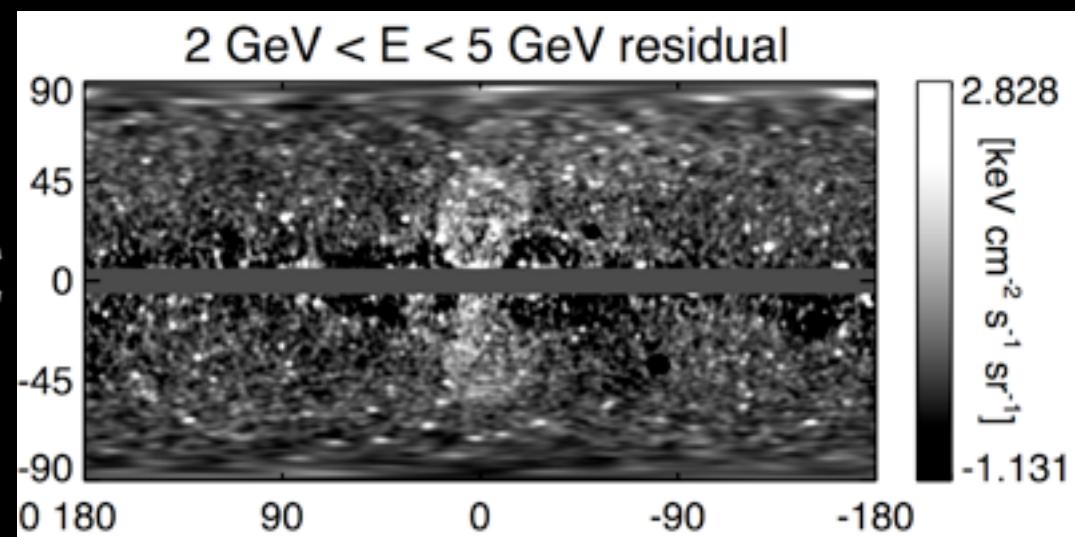
diffuse model 2-5 GeV



Fermi "haze/bubbles"



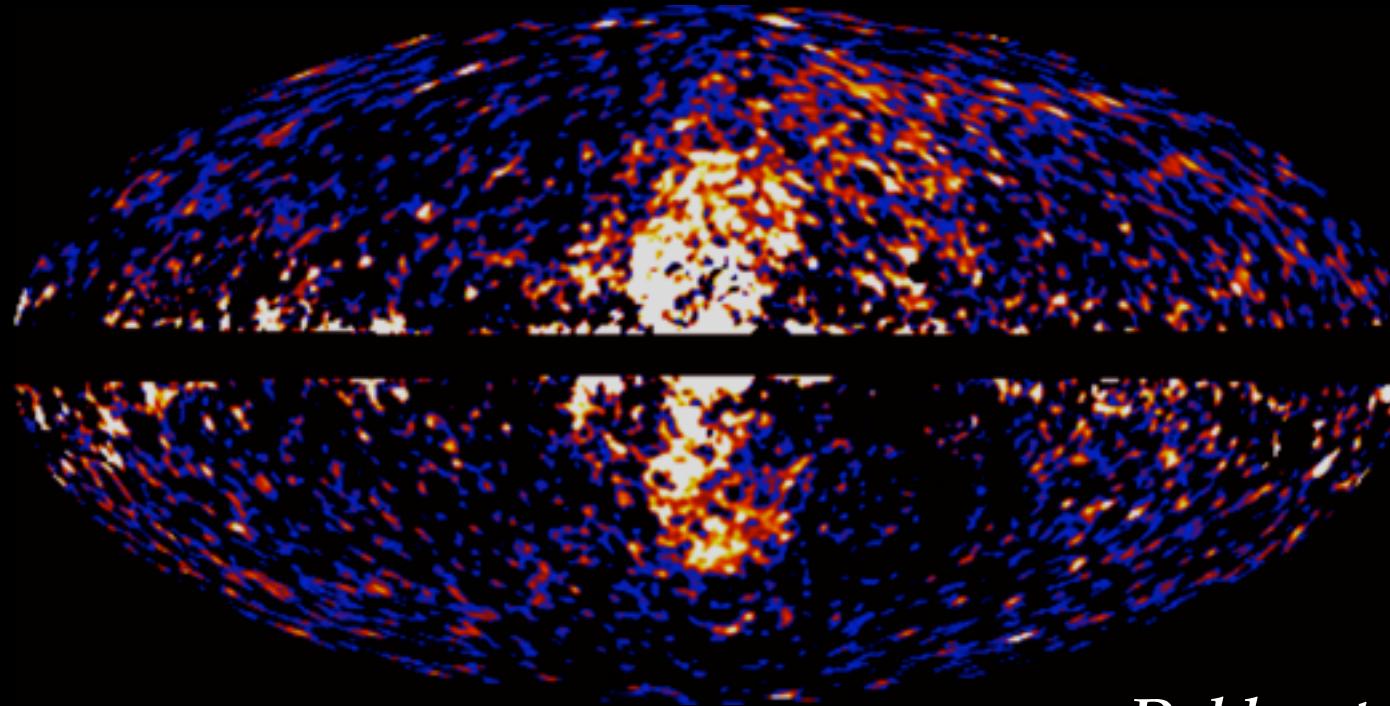
Dobler et al. (2010)



Fermi "haze"

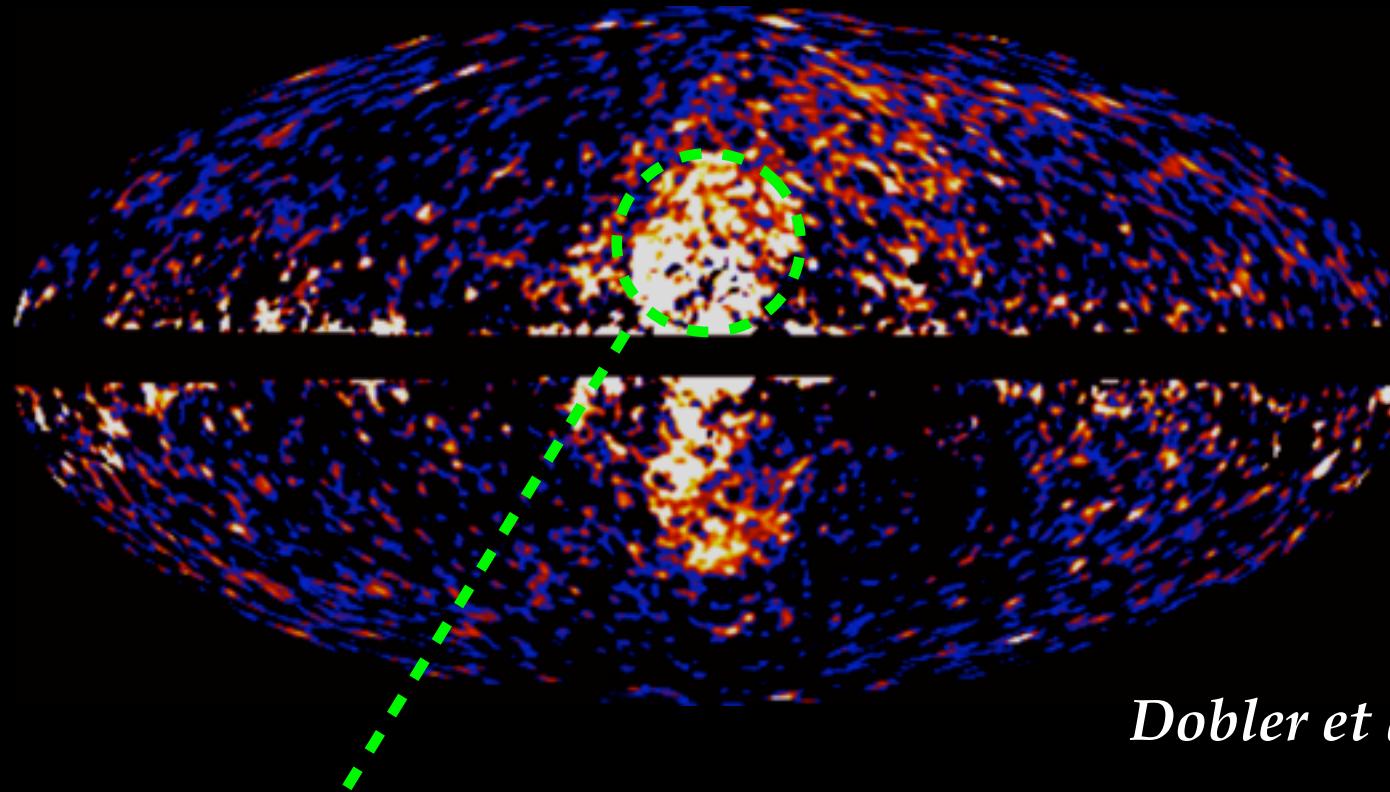
...and later the
"Fermi bubbles"
(Su et al., 2010)

the Fermi Haze a.k.a. Fermi Bubbles



Dobler et al. (2010)

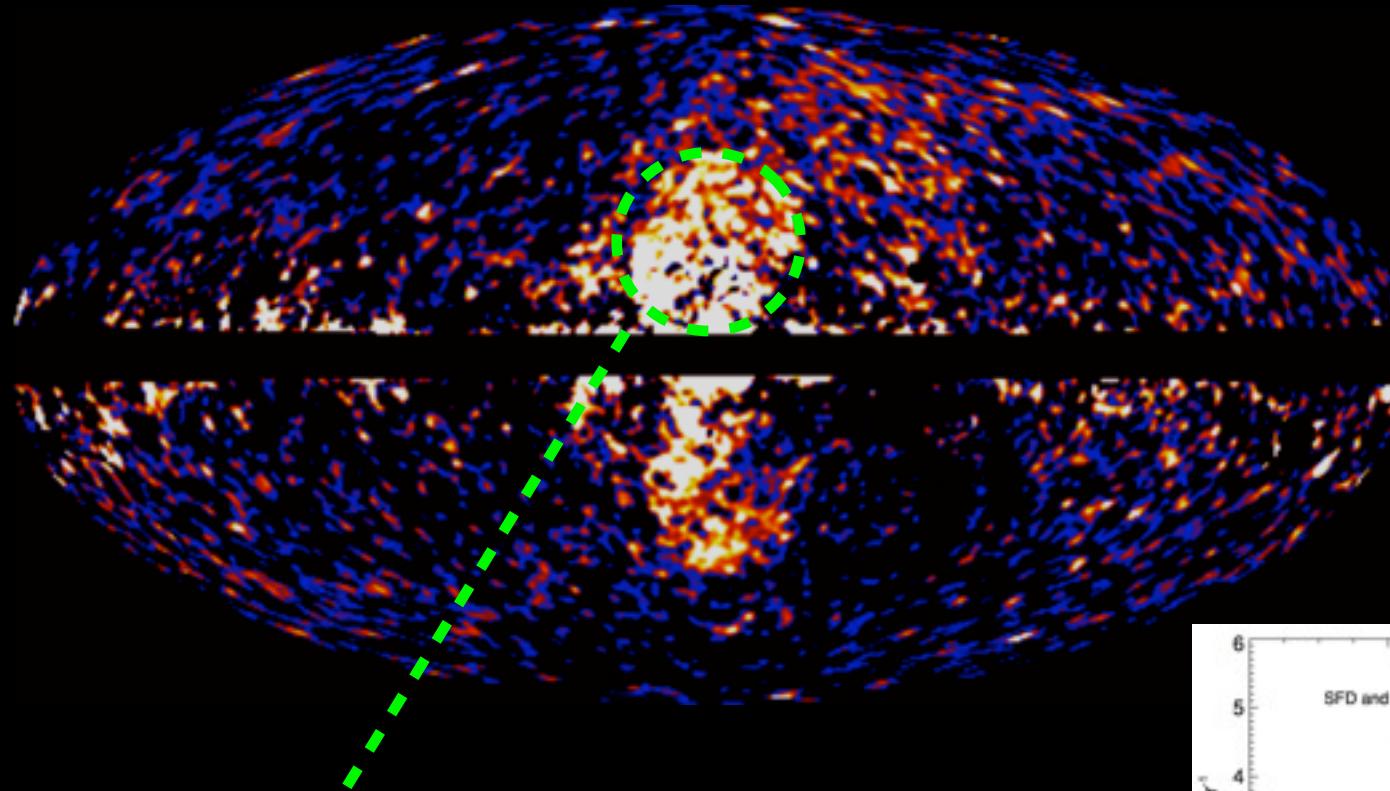
the Fermi Haze a.k.a. Fermi Bubbles



Dobler et al. (2010)

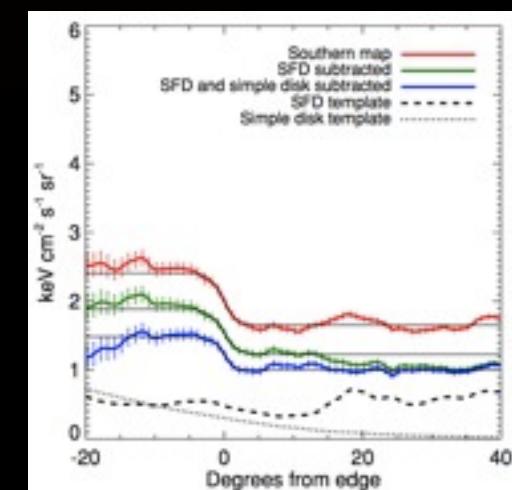
roughly “flat” brightness profile

the Fermi Haze a.k.a. Fermi Bubbles

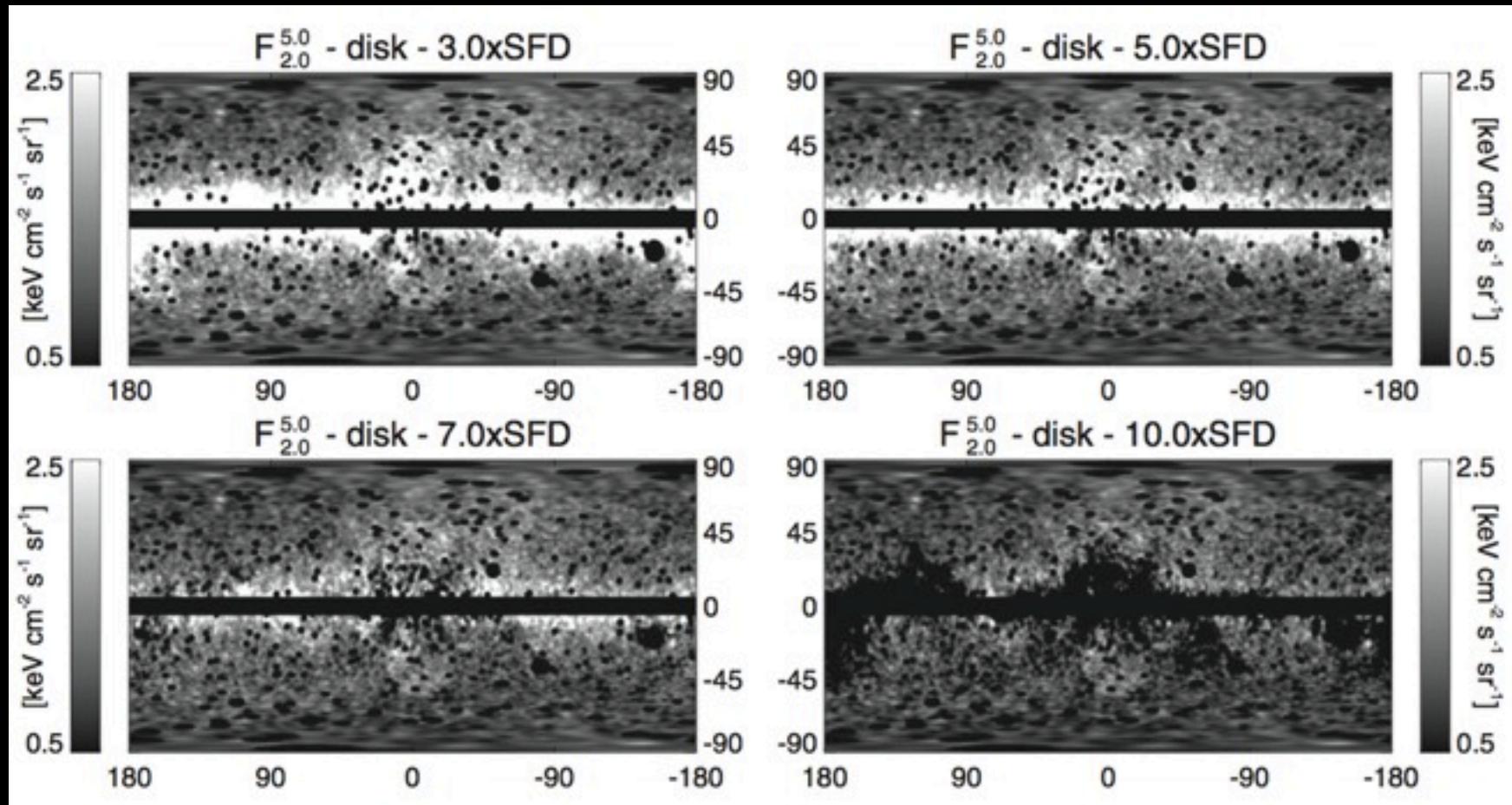


Su et al. (2010)

roughly “flat” brightness profile



morphological tracers of emission: CAUTION

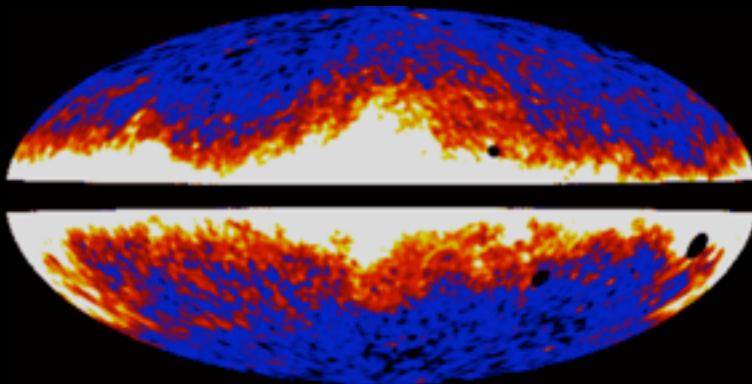


Dobler, Cholis, & Weiner (2011)

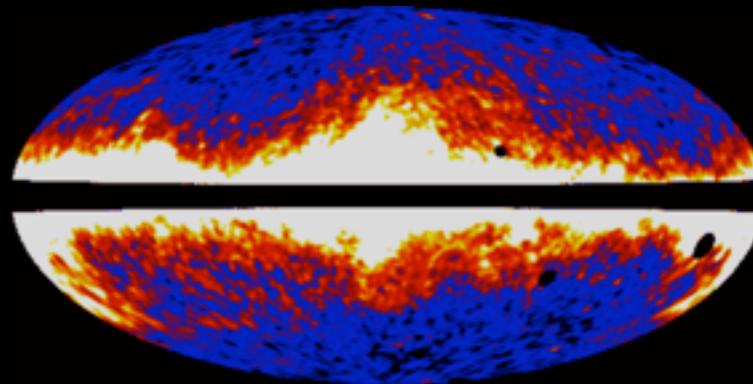
π^0 -to-dust column ratio varies with position,
especially towards the center of the Milky Way

the Fermi haze/bubbles

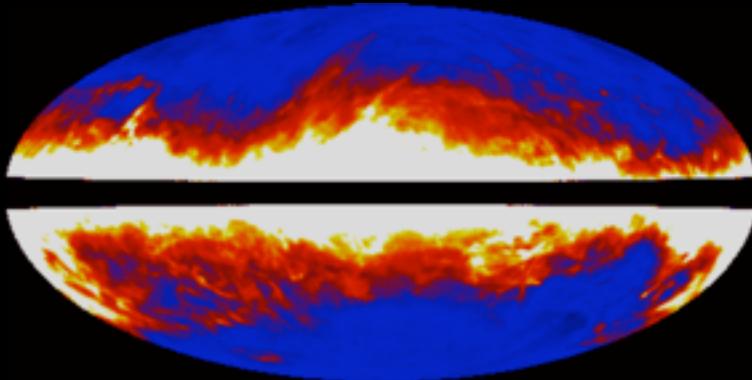
Fermi data 2-5 GeV



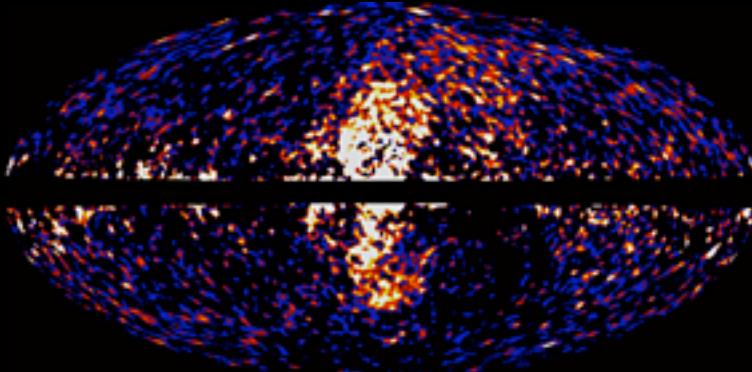
Fermi data 2-5 GeV



diffuse model 2-5 GeV

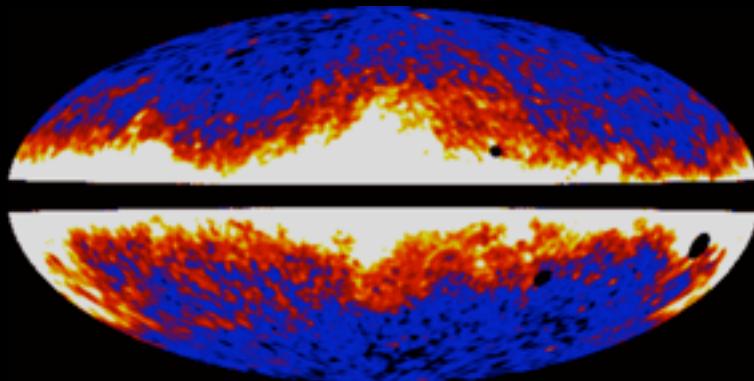


Fermi "haze/bubbles"

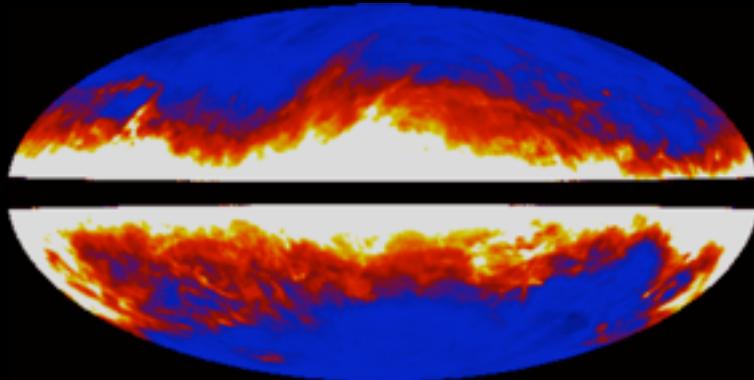


the Fermi haze/bubbles

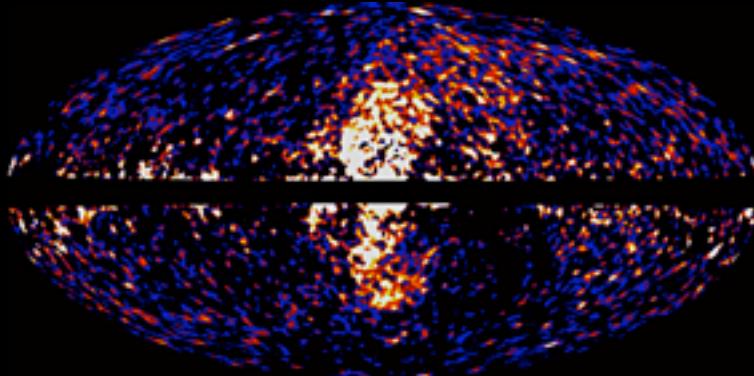
Fermi data 2-5 GeV



diffuse model 2-5 GeV

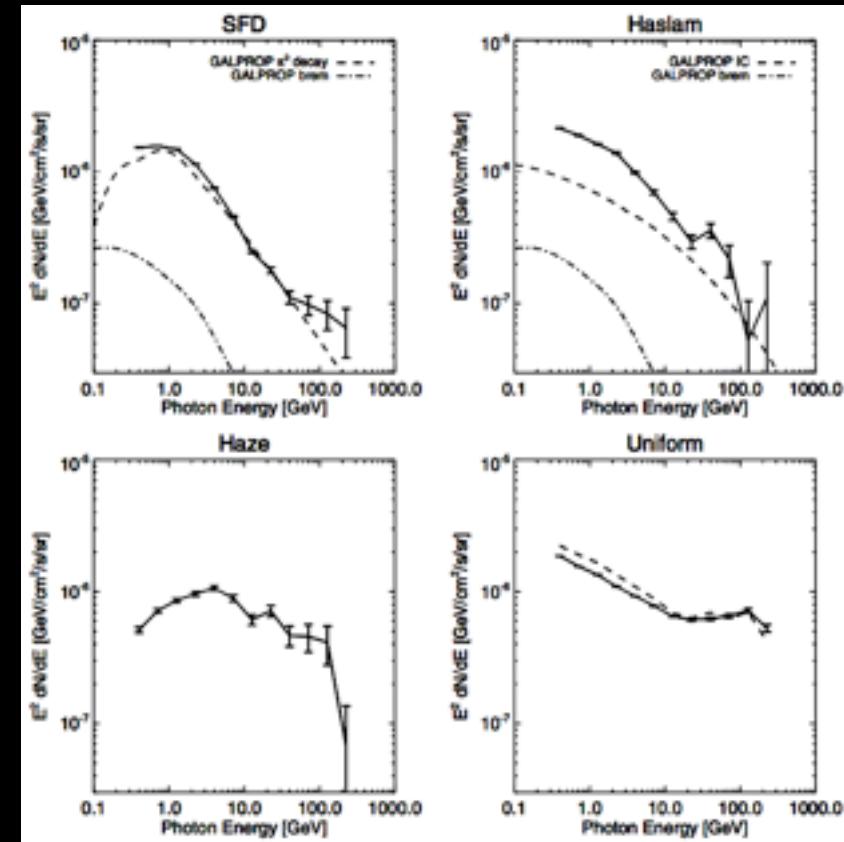


Fermi "haze/bubbles"



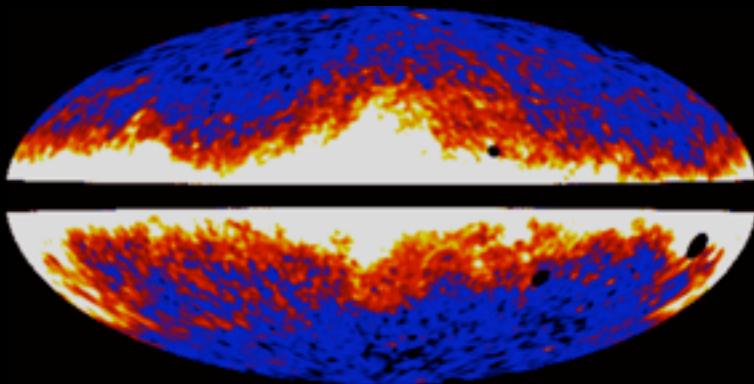
Fermi data 2-5 GeV

Dobler et al. (2010)

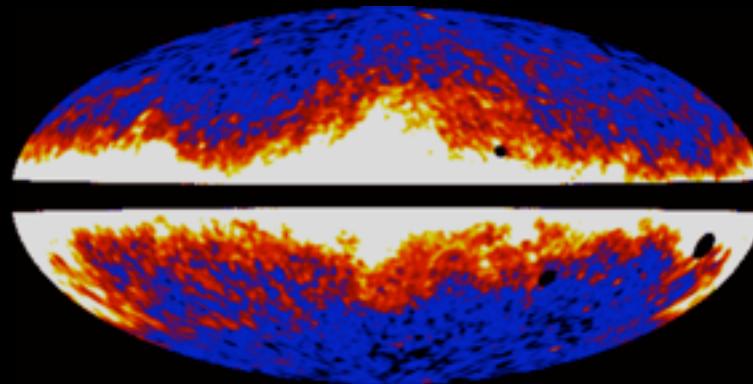


the Fermi haze/bubbles

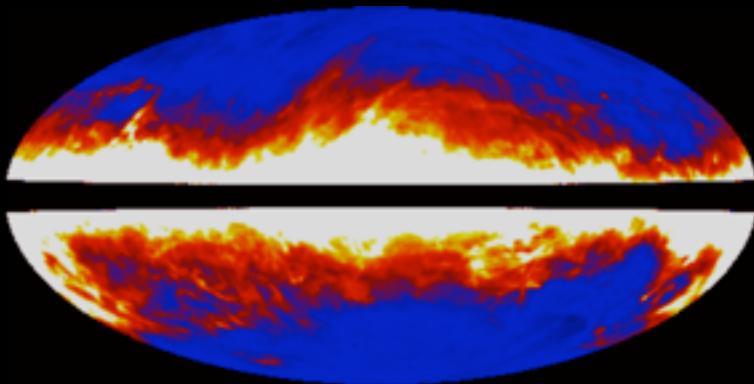
Fermi data 2-5 GeV



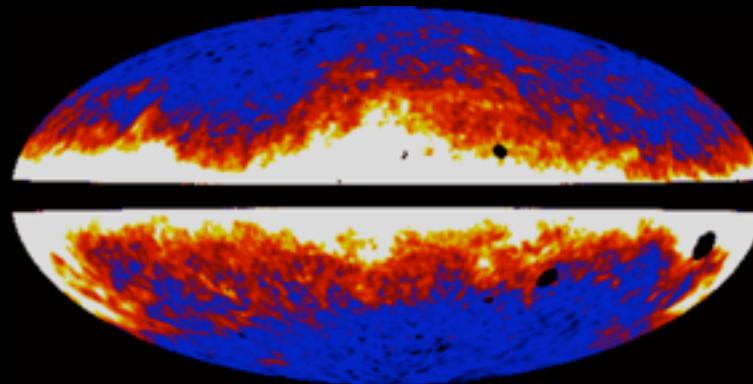
Fermi data 2-5 GeV



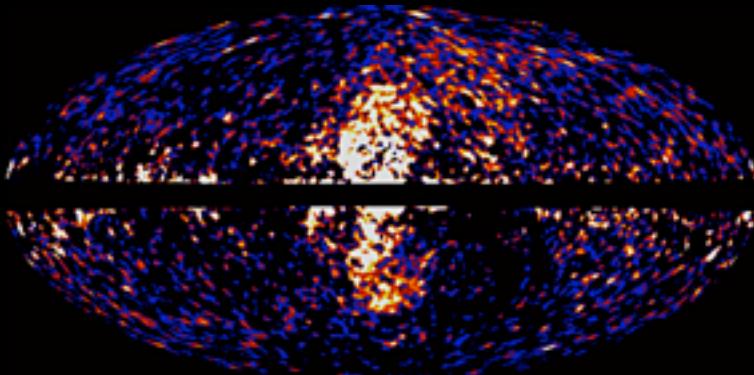
diffuse model 2-5 GeV



Fermi data 0.5-1 GeV

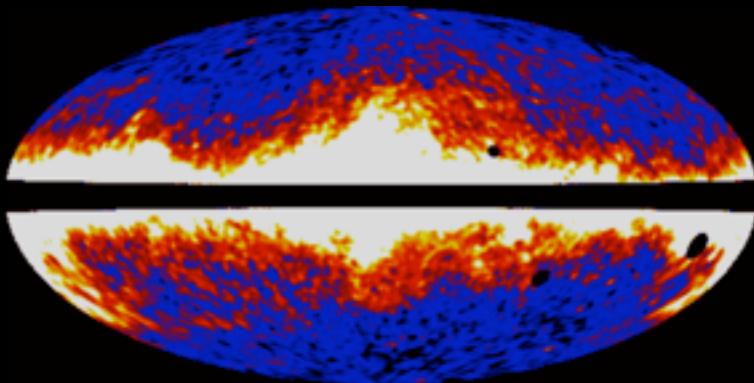


Fermi "haze/bubbles"

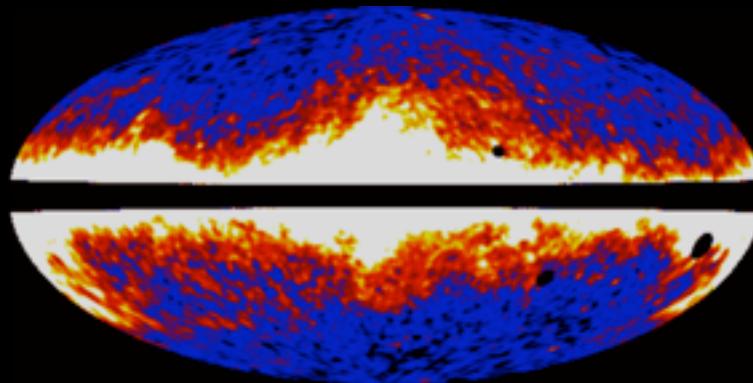


the Fermi haze/bubbles

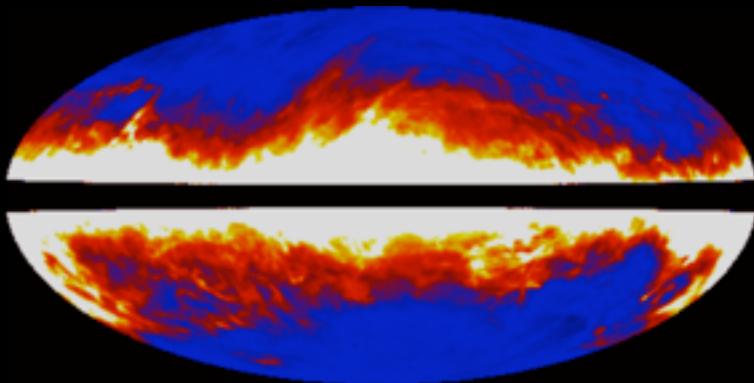
Fermi data 2-5 GeV



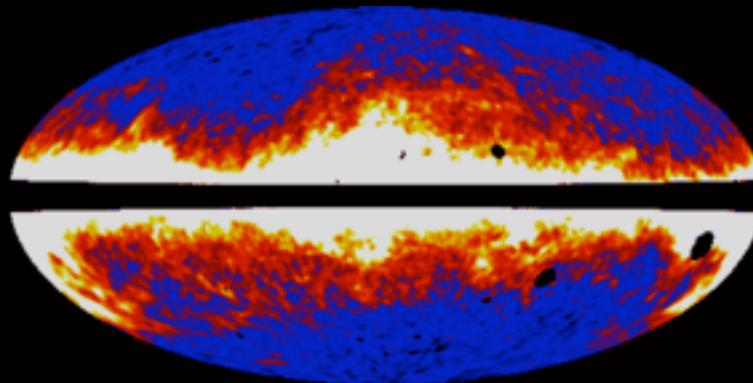
Fermi data 2-5 GeV



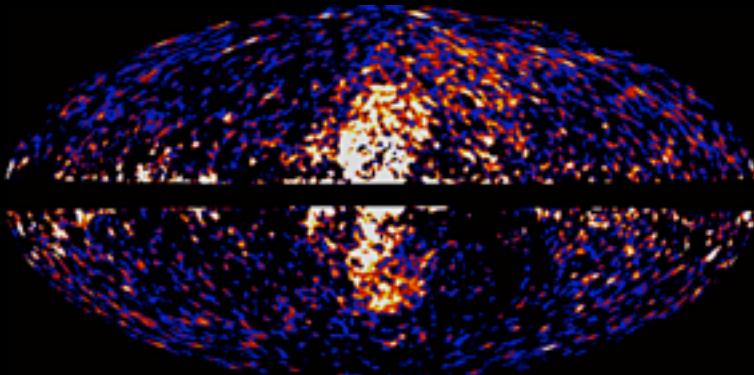
diffuse model 2-5 GeV



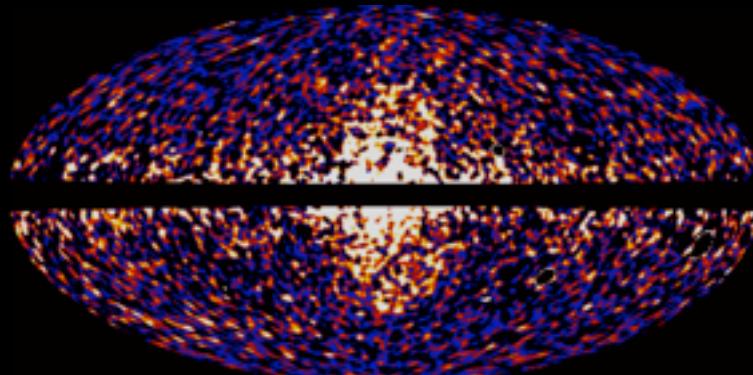
Fermi data 0.5-1 GeV



Fermi "haze/bubbles"

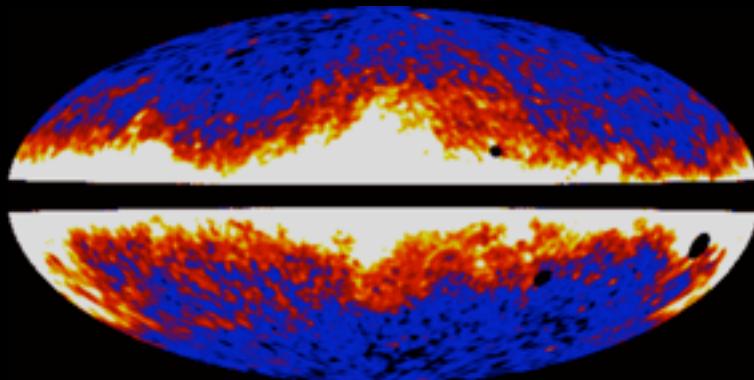


Fermi "haze/bubbles"

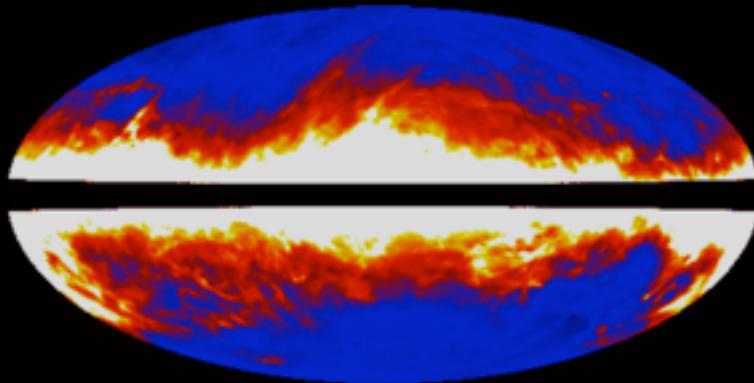


the Fermi haze/bubbles

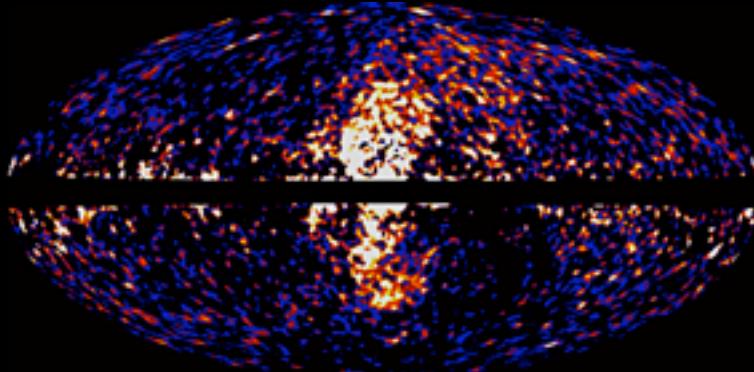
Fermi data 2-5 GeV



diffuse model 2-5 GeV

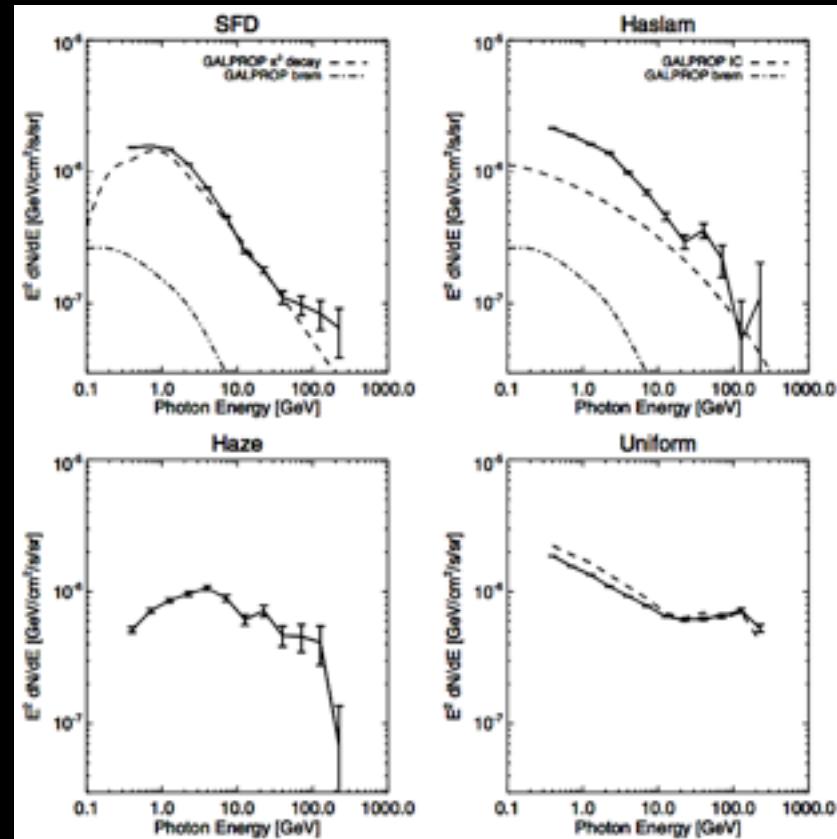


Fermi "haze/bubbles"

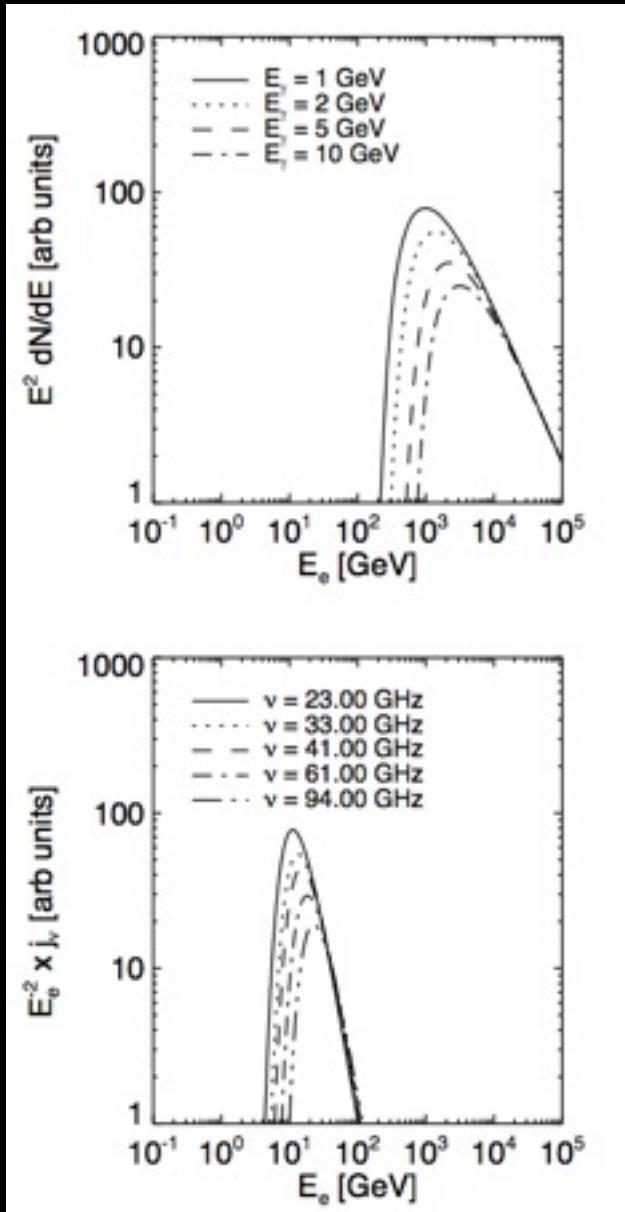


Fermi data 2-5 GeV

Dobler et al. (2010)



electron spectra



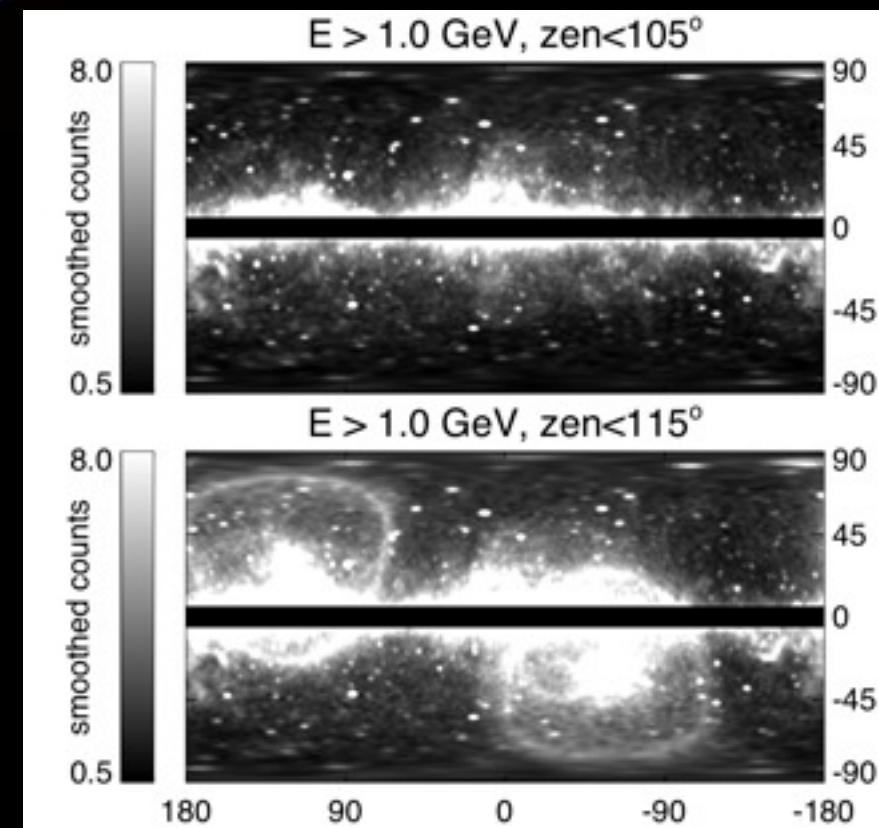
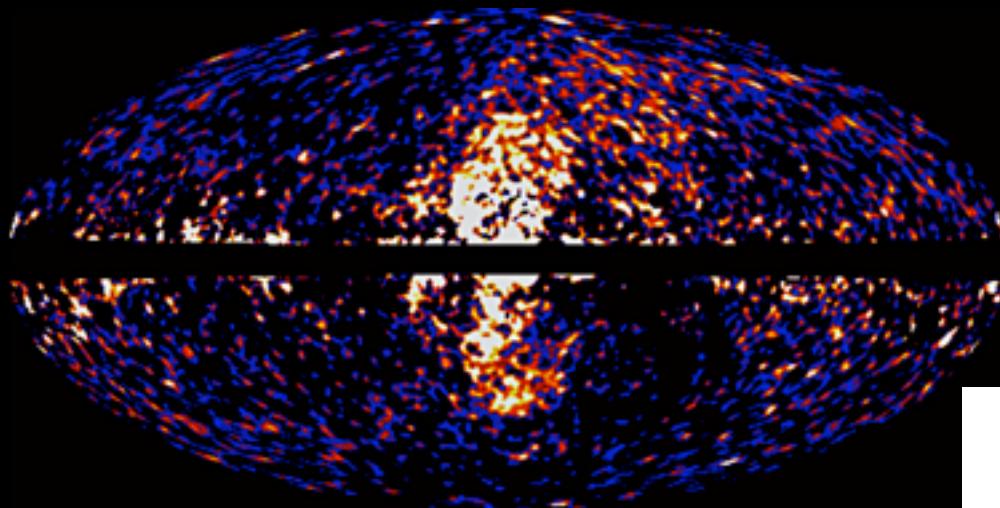
- . the same spectrum (normalization and slope) reproduces the **microwave** and **gamma-ray** emission

$$dN/dE \propto E^{-2.0}$$

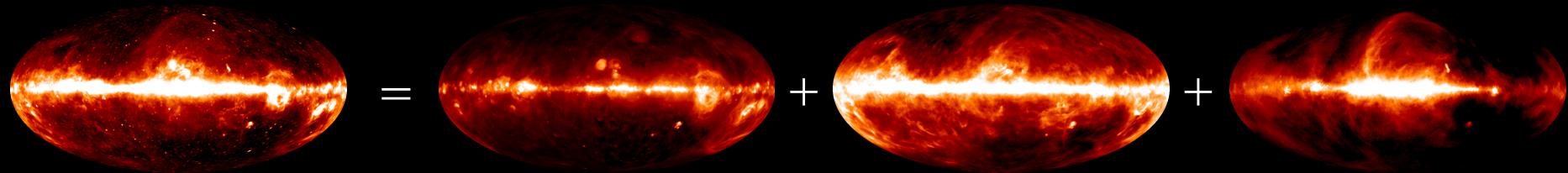
- . the characteristic energy of the emitting electrons for microwaves is $E_e \sim 10$ GeV but for gammas is $E_e \sim 1$ TeV

- . this implies **very little cooling** of the cosmic-ray population

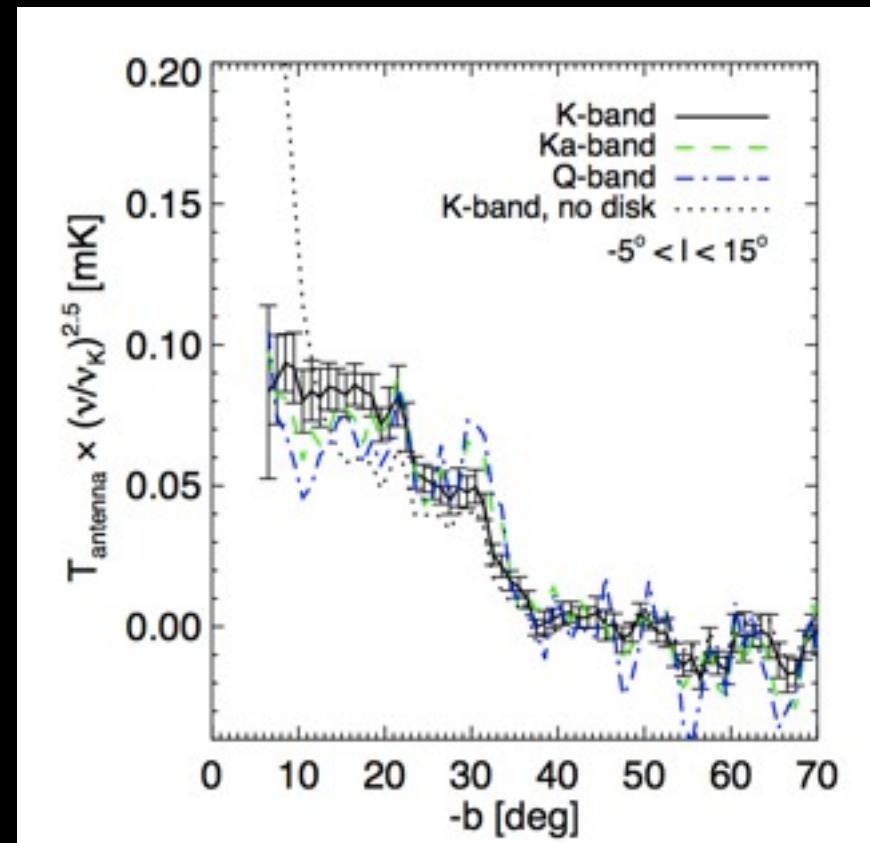
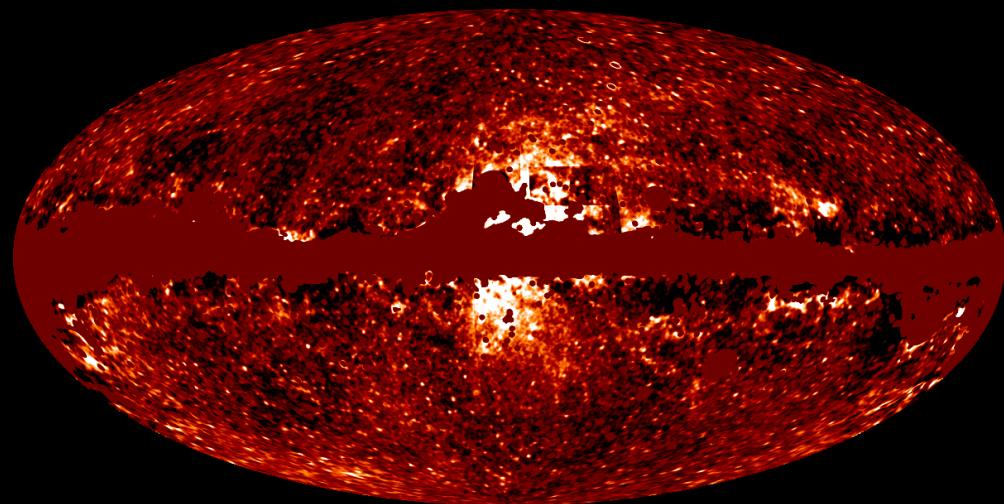
are the edges “real”?



$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

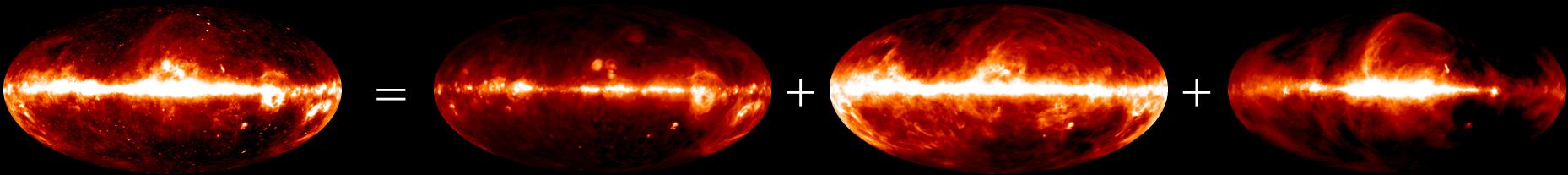


23 GHz haze

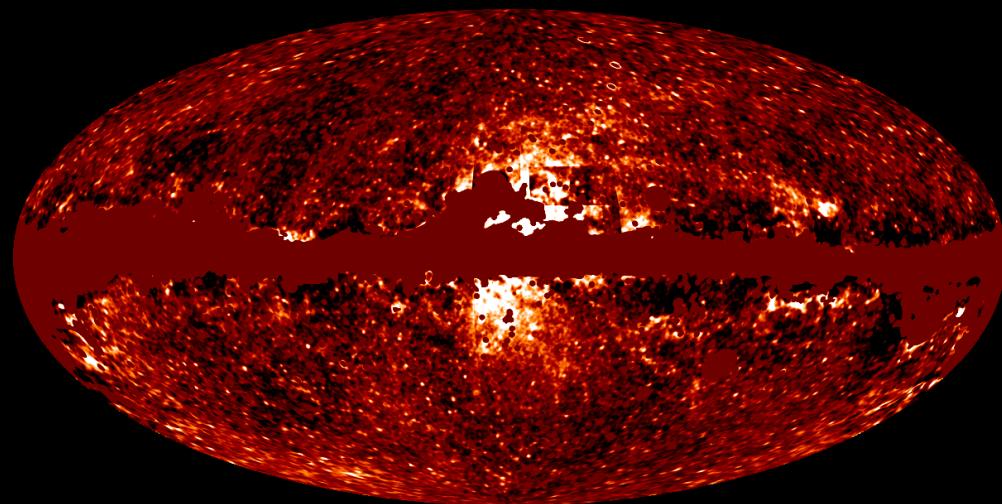


Dobler (2012)

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

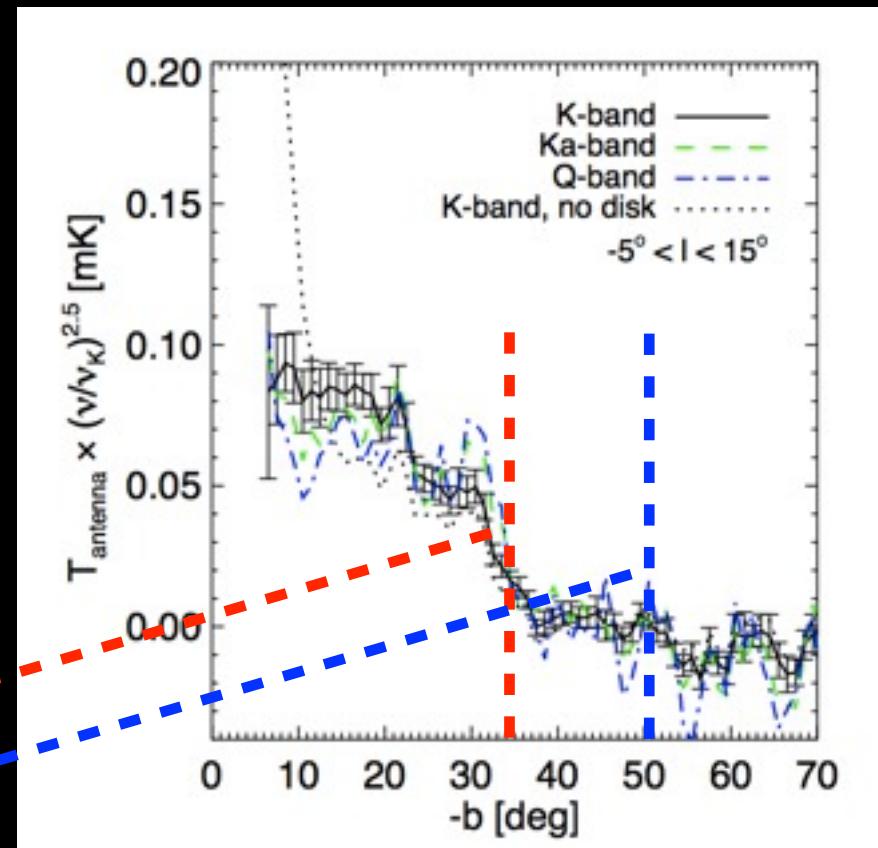


23 GHz haze



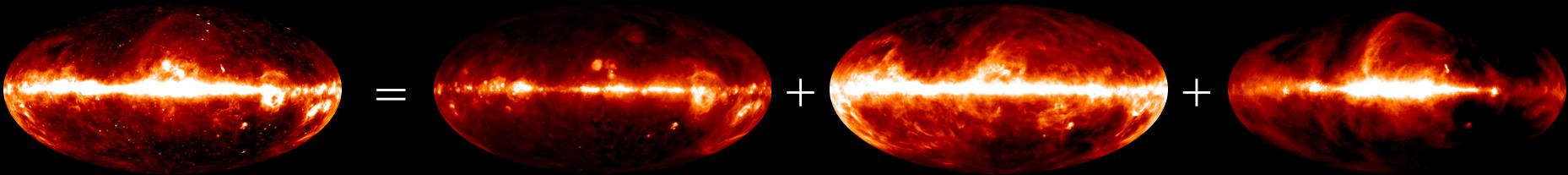
WMAP “drops” here ($b \sim -35^\circ$)

Fermi “cuts off” here ($b \sim -50^\circ$)

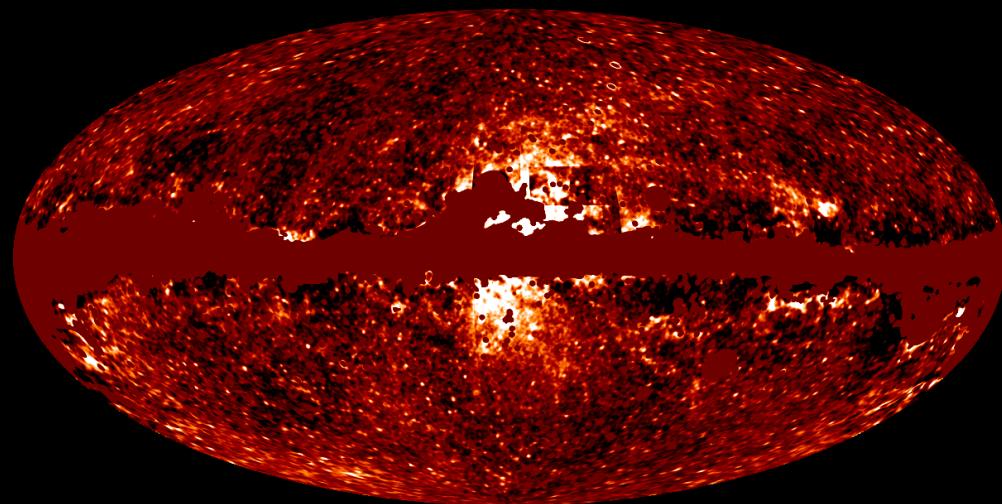


Dobler (2012)

$$\mathbf{a}_\nu = (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{P})^{-1} (\mathbf{P}^T \mathbf{n}_\nu^{-1} \mathbf{d}_\nu)$$

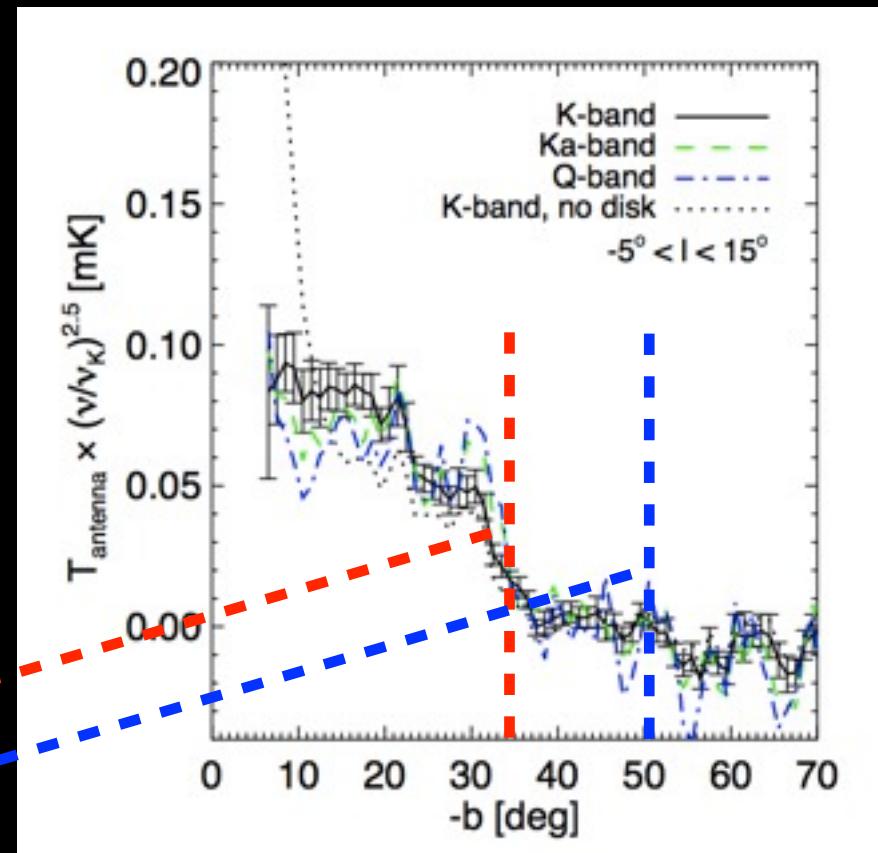


23 GHz haze



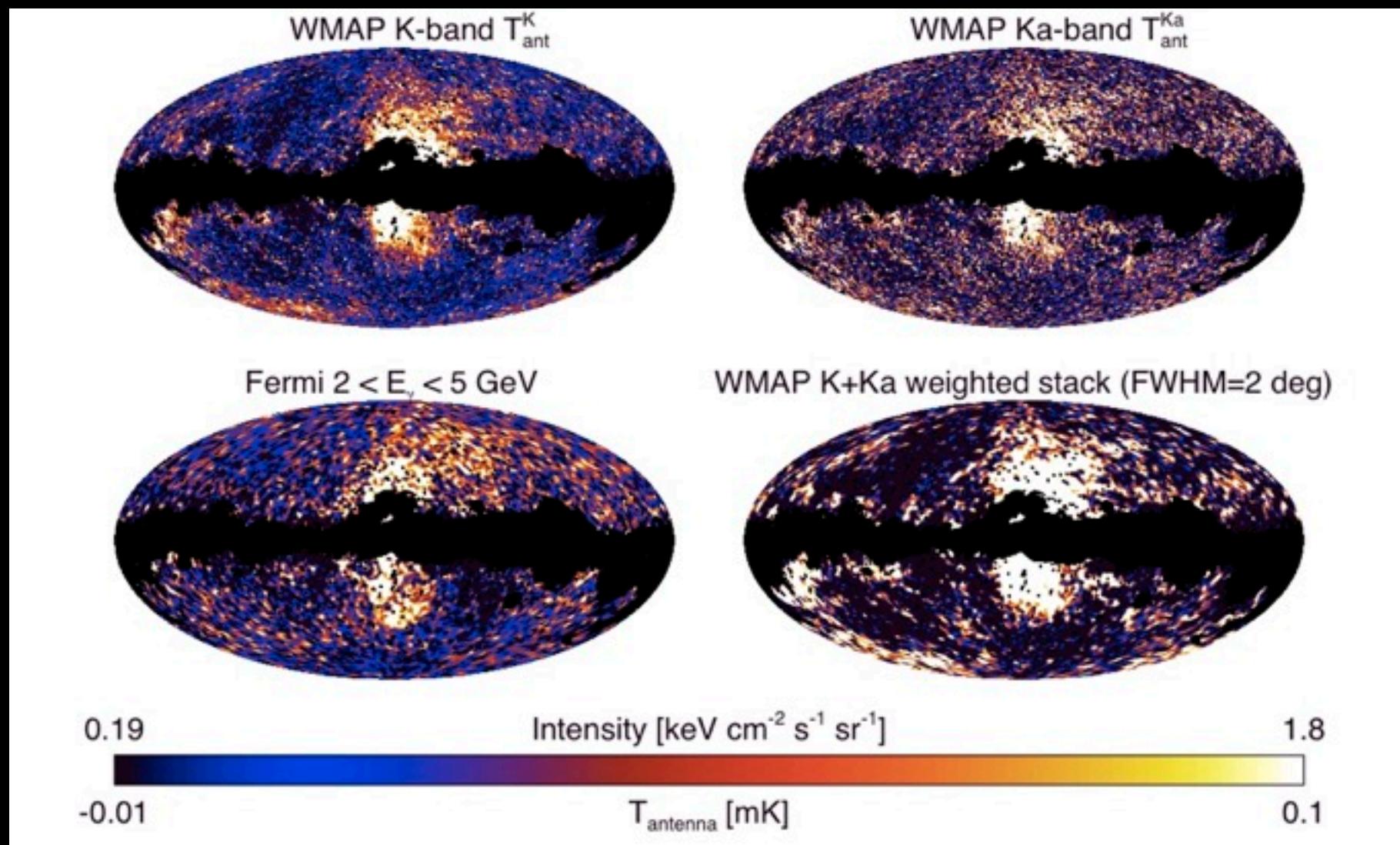
WMAP “drops” here ($b \sim -35^\circ$)

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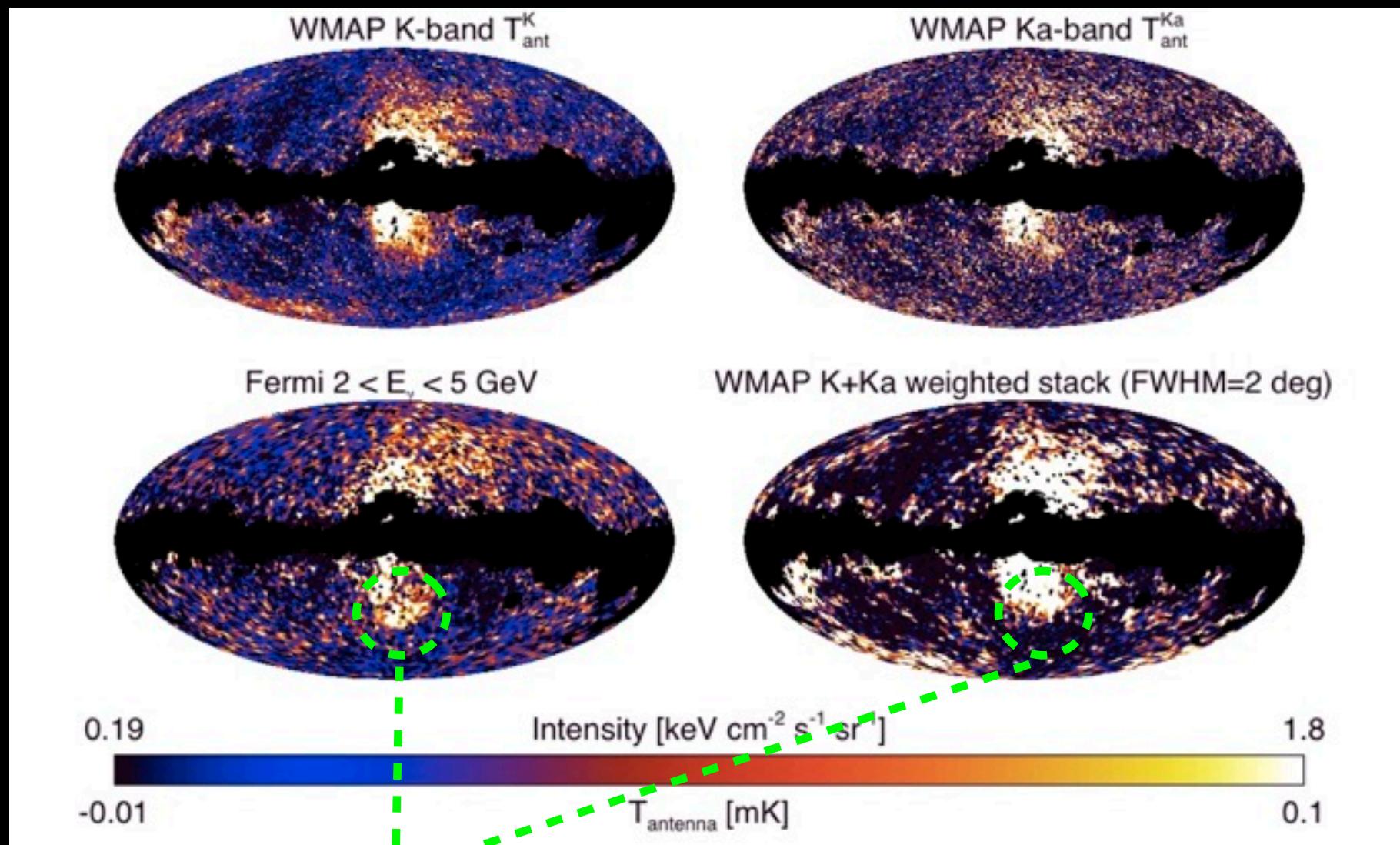


are they the same structure? are the *Fermi* edges “real”? Dobler (2012)

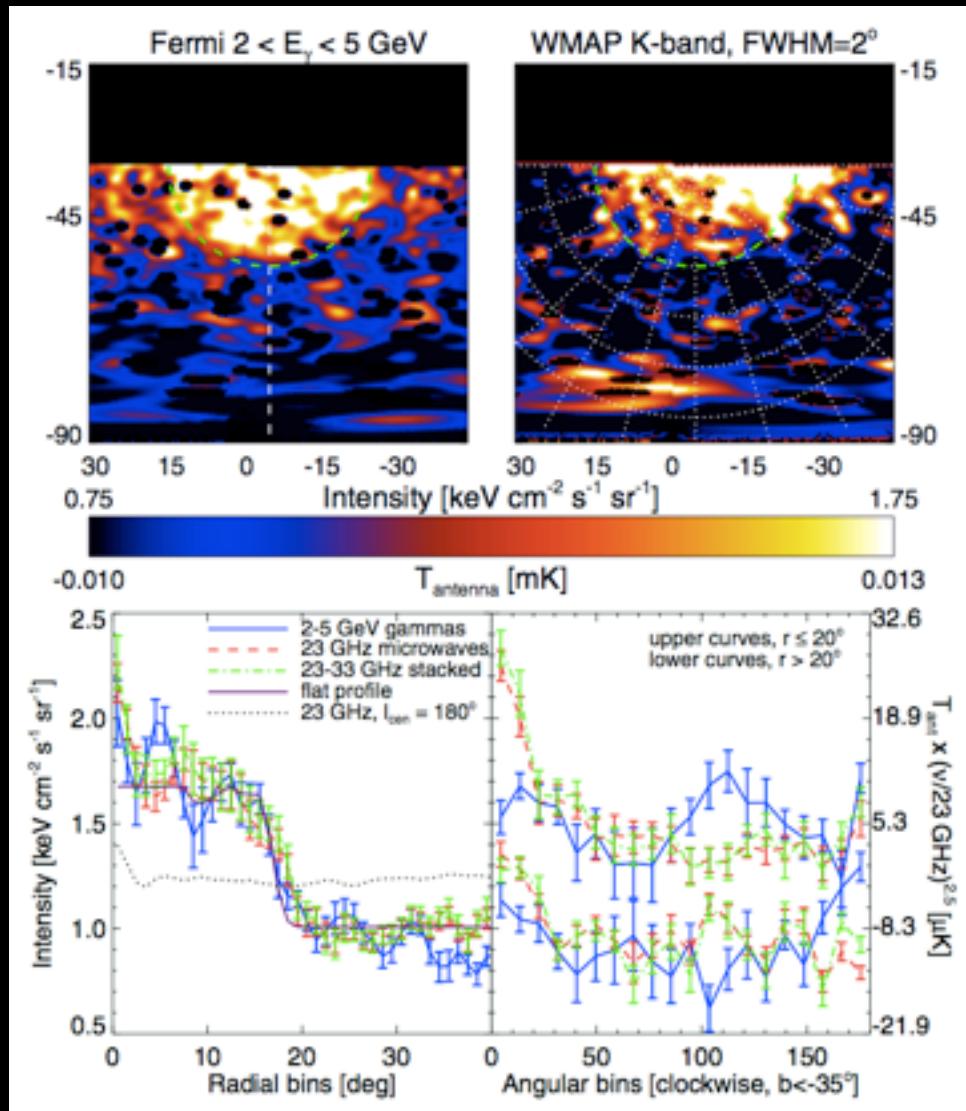
Dobler (2012b)



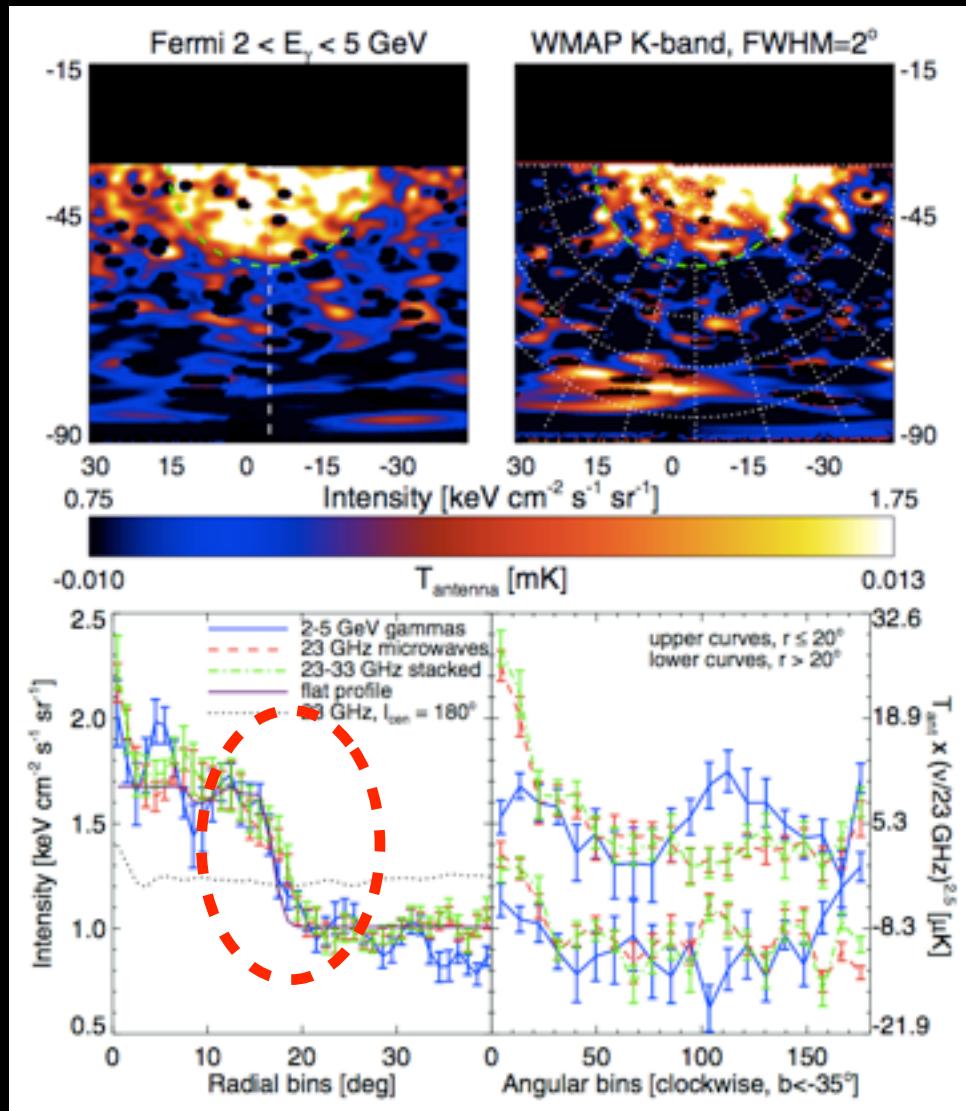
are they the same structure? are the *Fermi* edges “real”?

Dobler (2012b)

coincident “edge”?

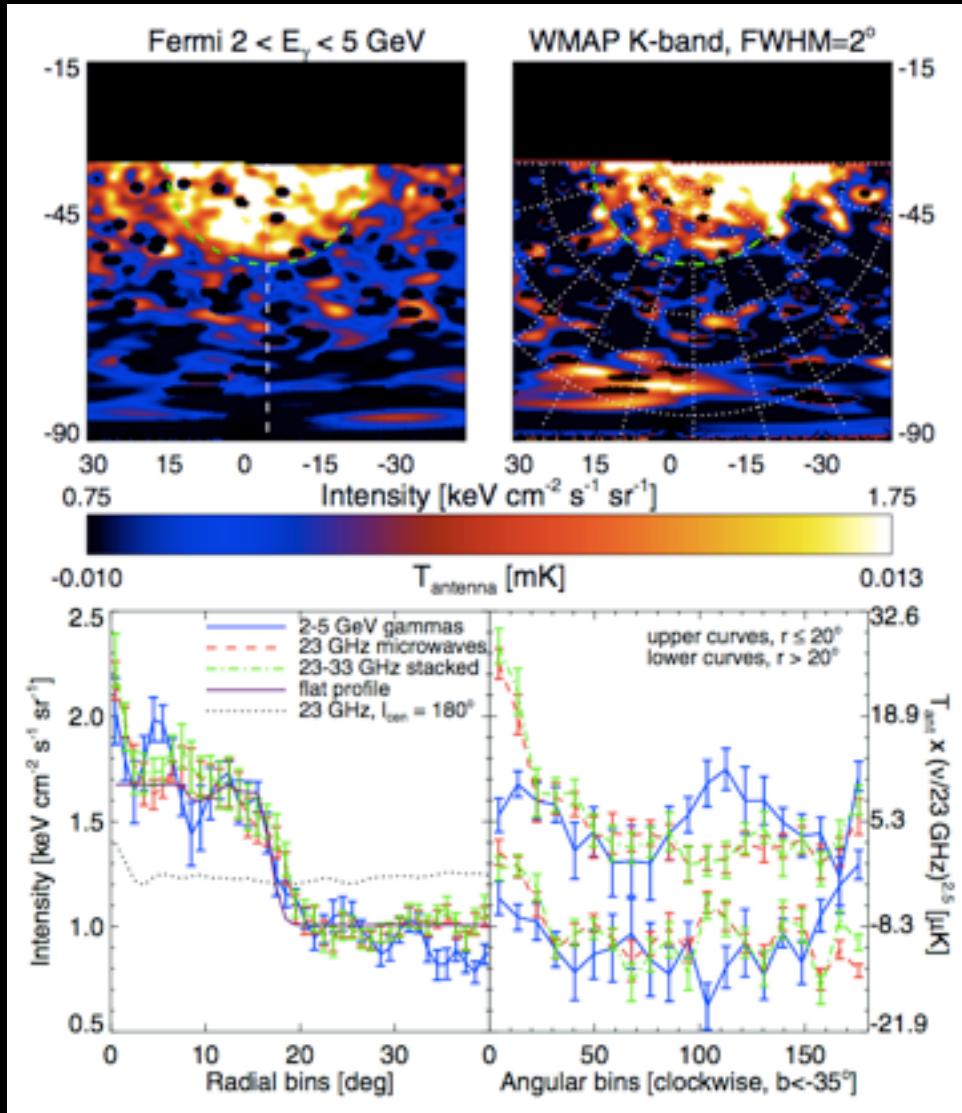
Dobler (2012b)

coincident “edge”? YES!

Dobler (2012b)

coincident “edge”? YES!

Dobler (2012b)



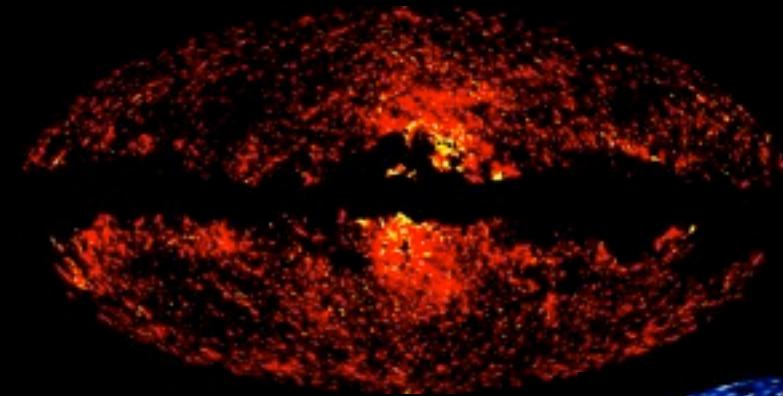
independent confirmation that the *Fermi* Haze/Bubbles edges are *real*

demonstrates conclusively that the microwave and gamma-ray haze/bubbles are the *same structure* observed at multiple wavelengths

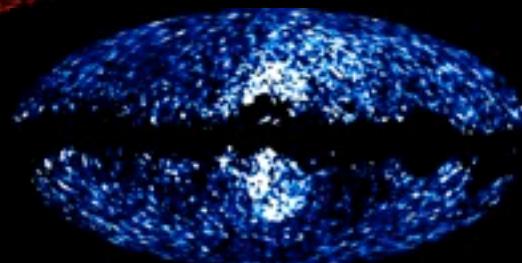
strongly suggests an inverse Compton origin for the gamma-ray emission and that the microwave emission represents a ***separate component*** of diffuse synchrotron

coincident “edge”? YES!

Planck

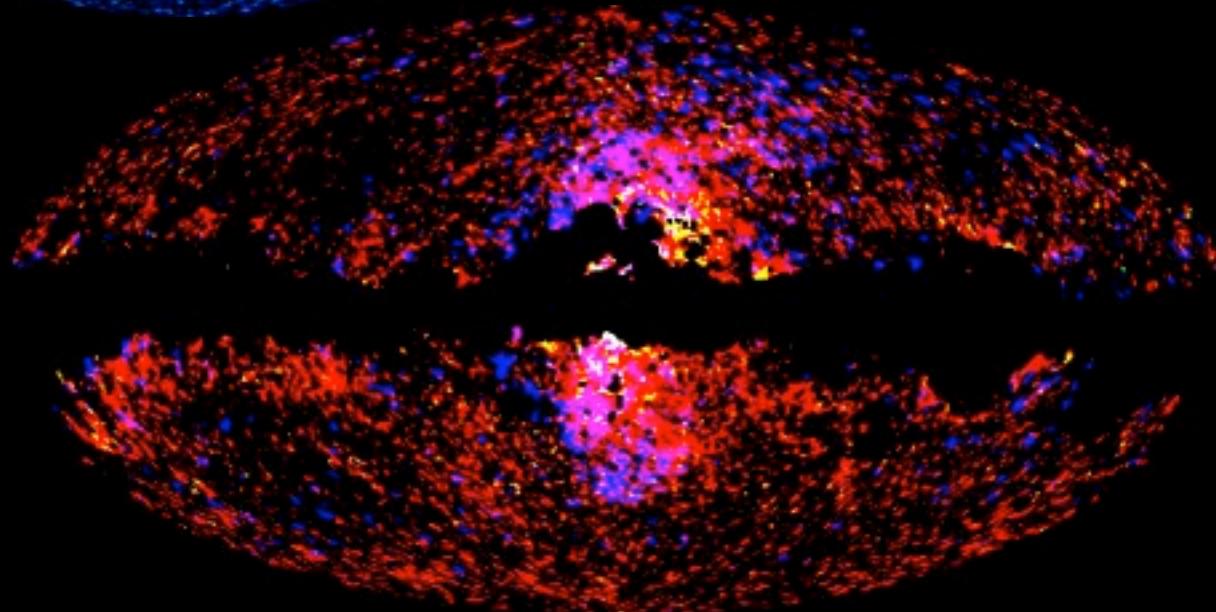


The Galactic haze/bubbles is shown here in *PLANCK* data from 30-44 GHz

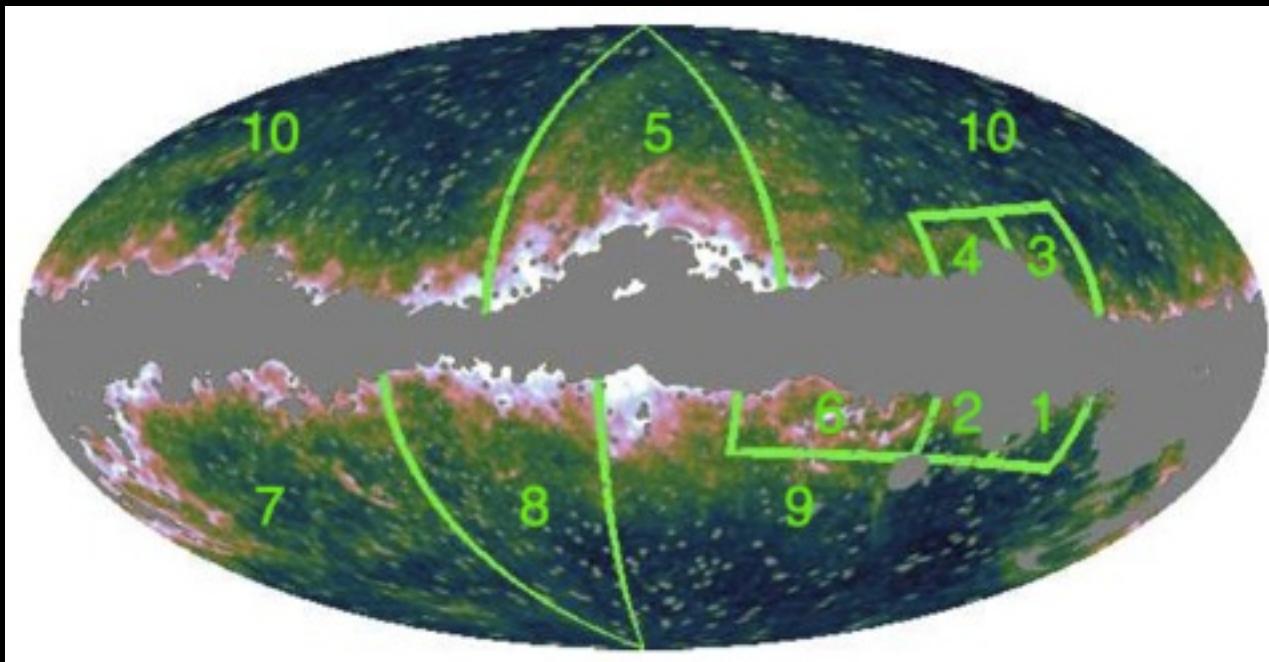


The same structure at 2-5 GeV as seen by the *Fermi Gamma-Ray Space Telescope*

A multi-wavelength composite image showing both microwaves and gamma-rays: *PLANCK* 30 GHz (red), 44 GHz (green), and *Fermi* 2-5 GeV (blue).

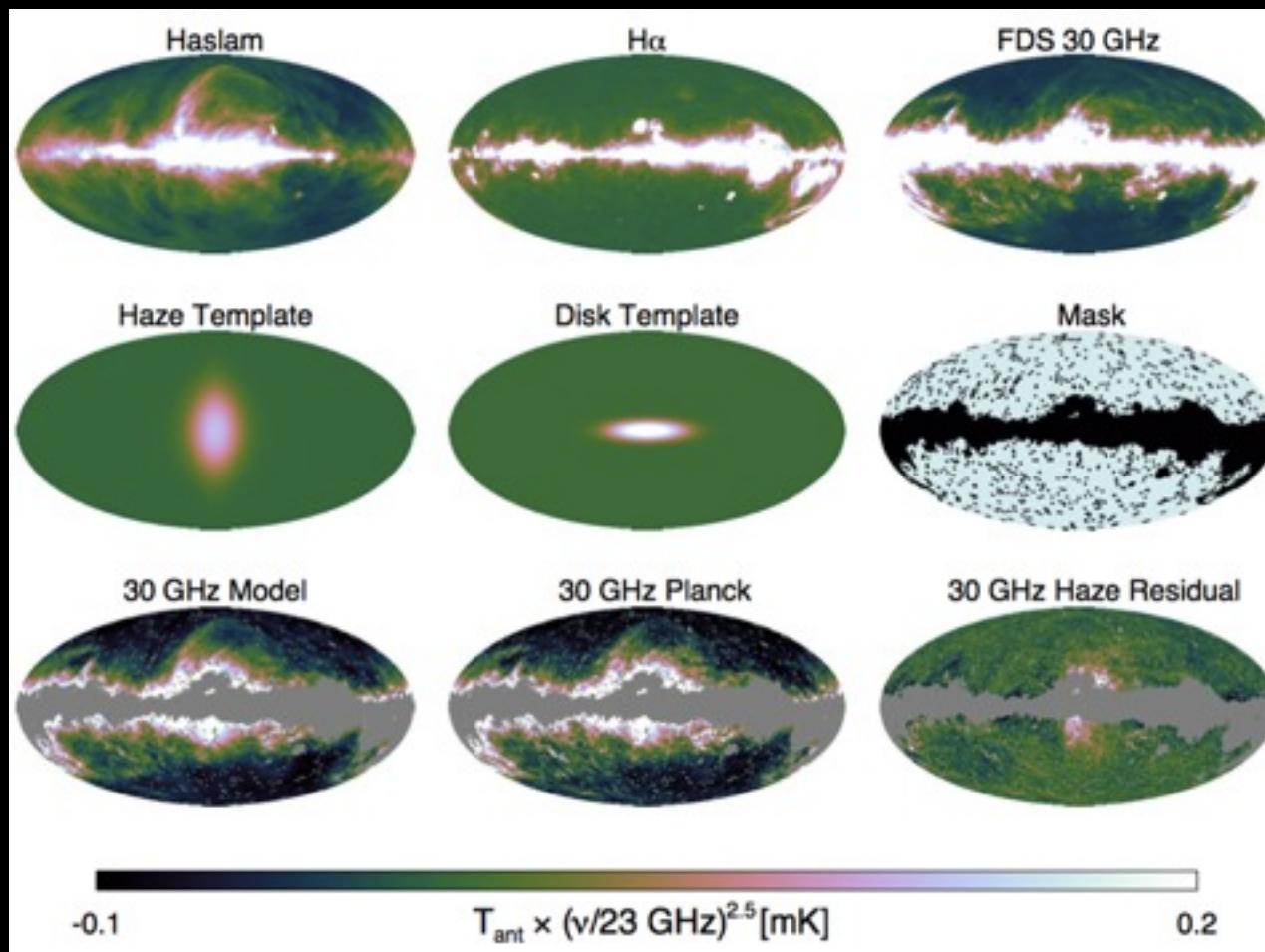


Planck



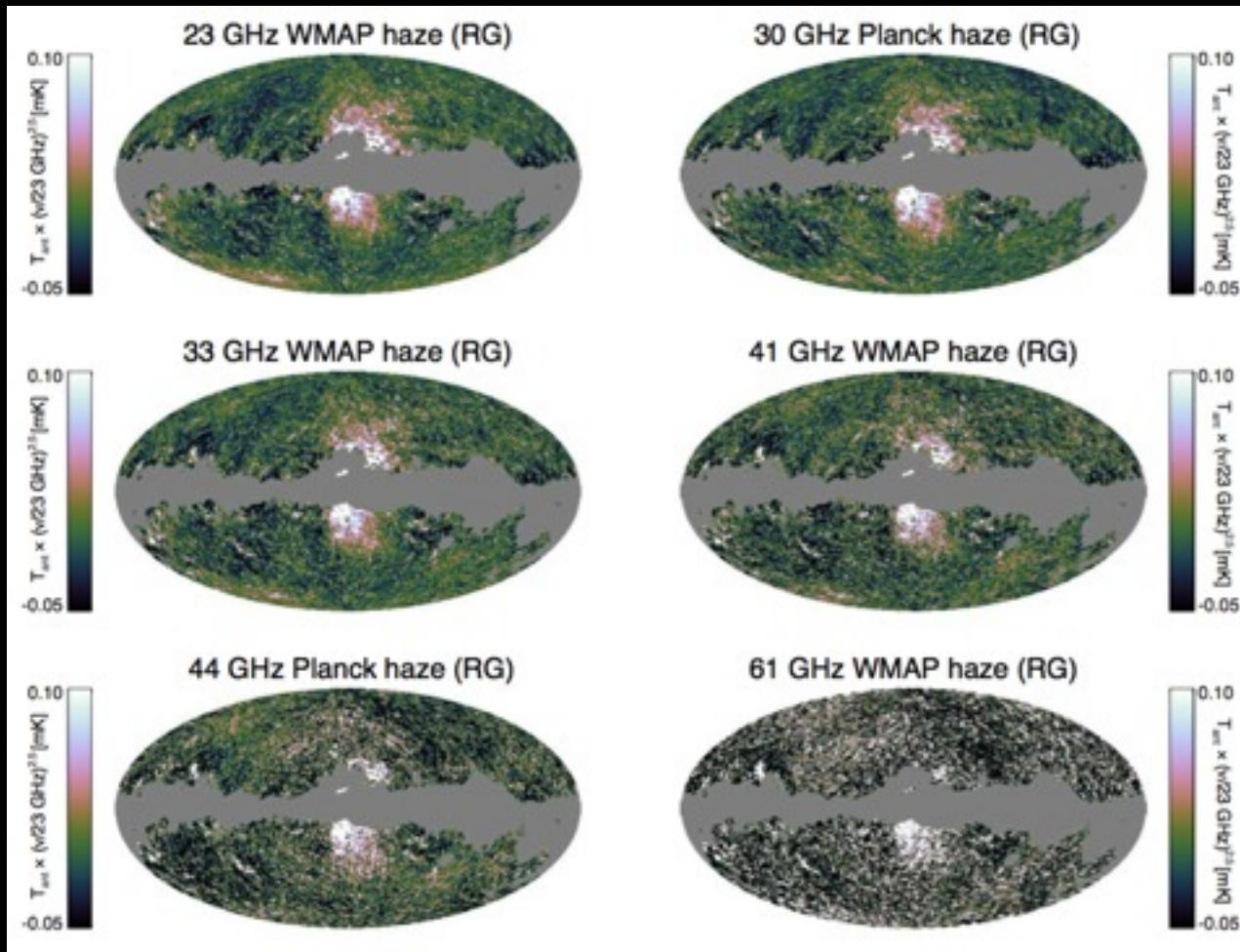
. divide sky into 10 regions

Planck



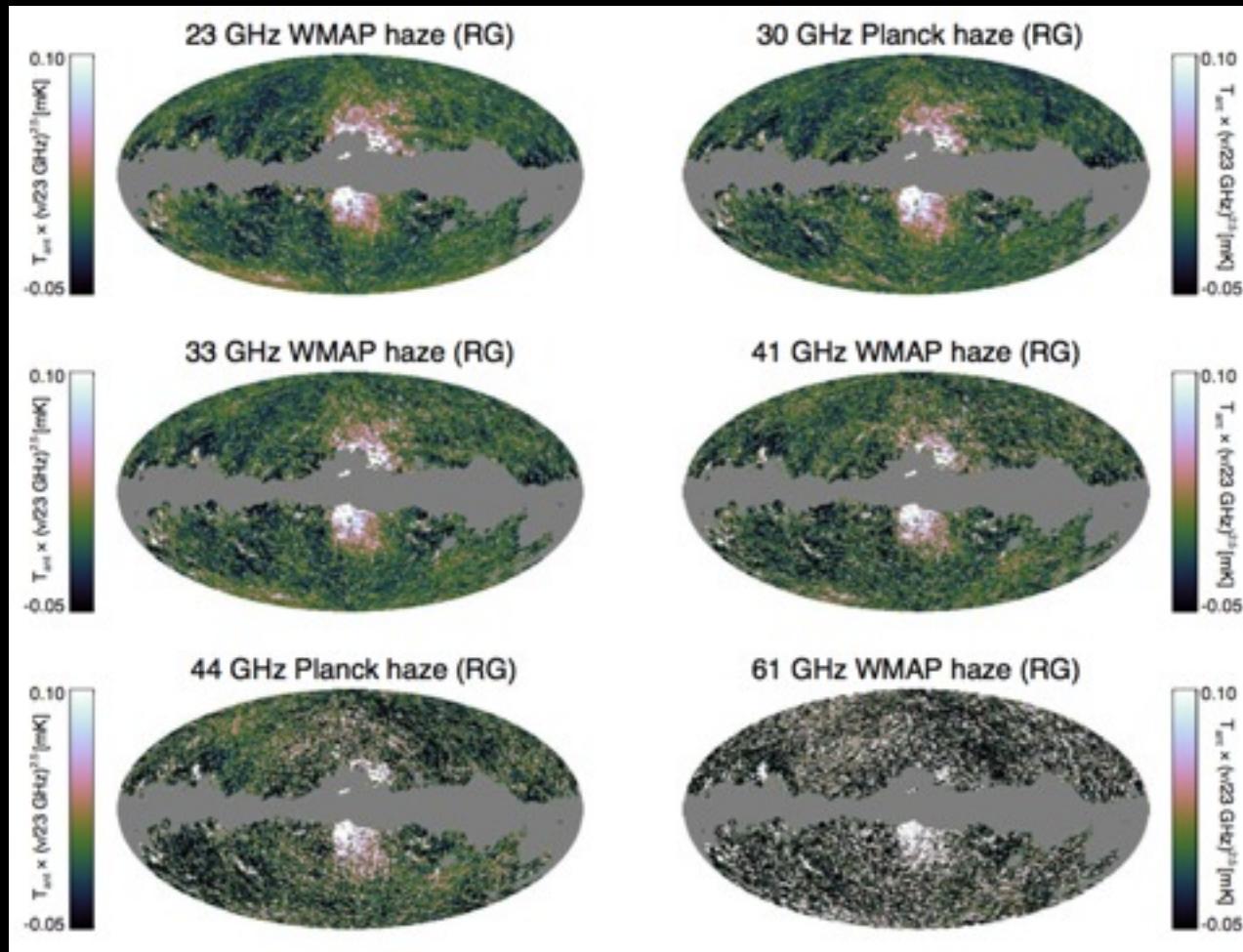
- . divide sky into 10 regions
- . five template fit to the data on each region independently
- . “stitch” together to form a full sky model and residual map

Planck



- . divide sky into 10 regions
- . five template fit to the data on each region independently
- . “stitch” together to form a full sky model and residual map
- . apply multi-template, multi-region fit to each *Planck* and *WMAP* band

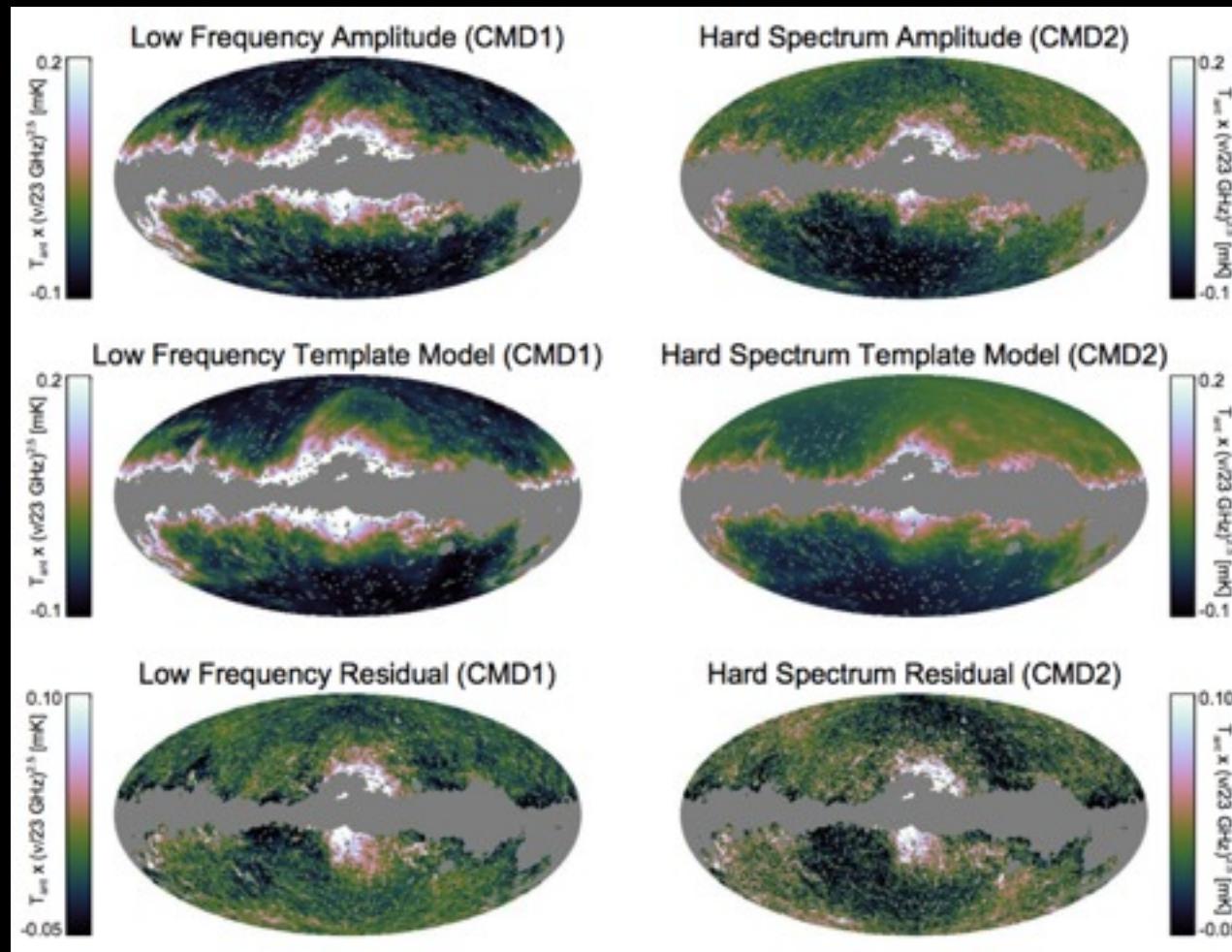
Planck



- . divide sky into 10 regions
- . five template fit to the data on each region independently
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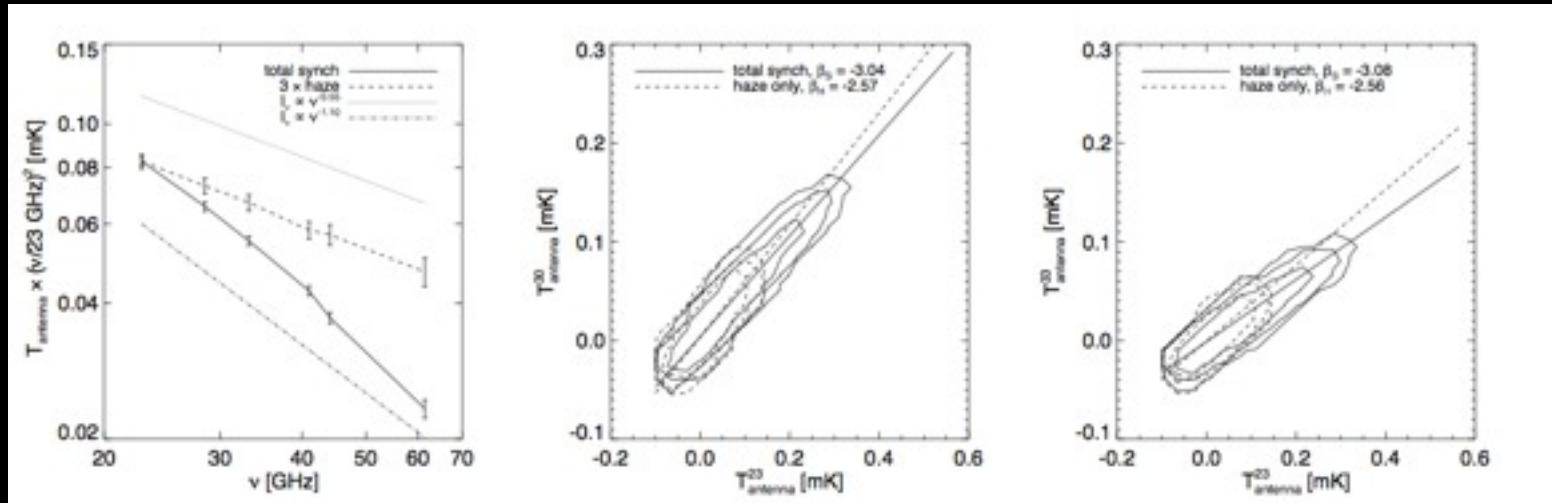
$\nu^{2.5}$ scaling yields roughly constant brightness with frequency

Planck



Bayesian/Gibbs haze residual

Planck

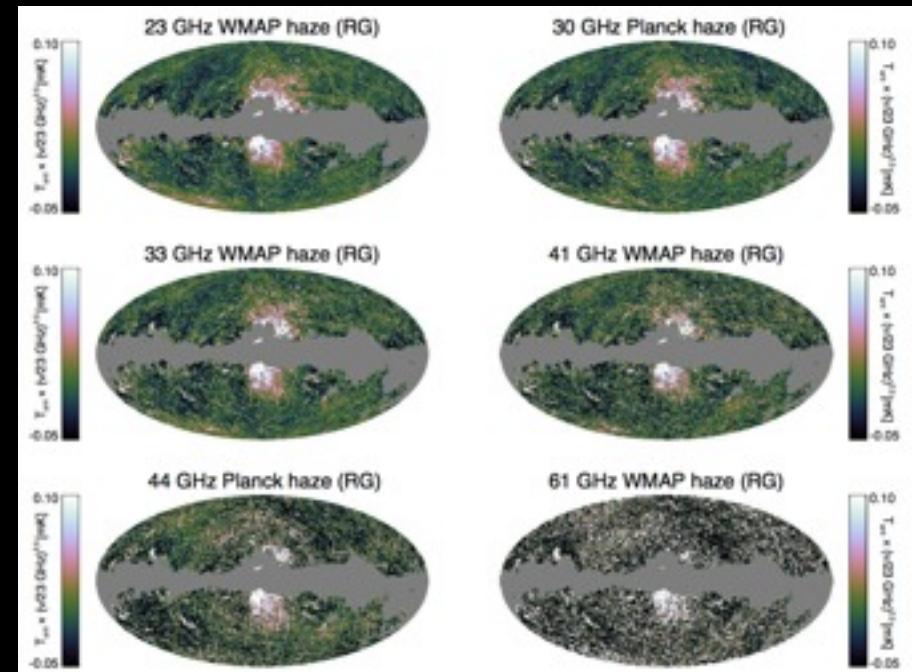


Planck wavelength coverage allows us to measure the spectrum of the haze/bubbles residual to high precision from $\sim 20\text{-}61\text{ GHz}$ and with little systematic bias:

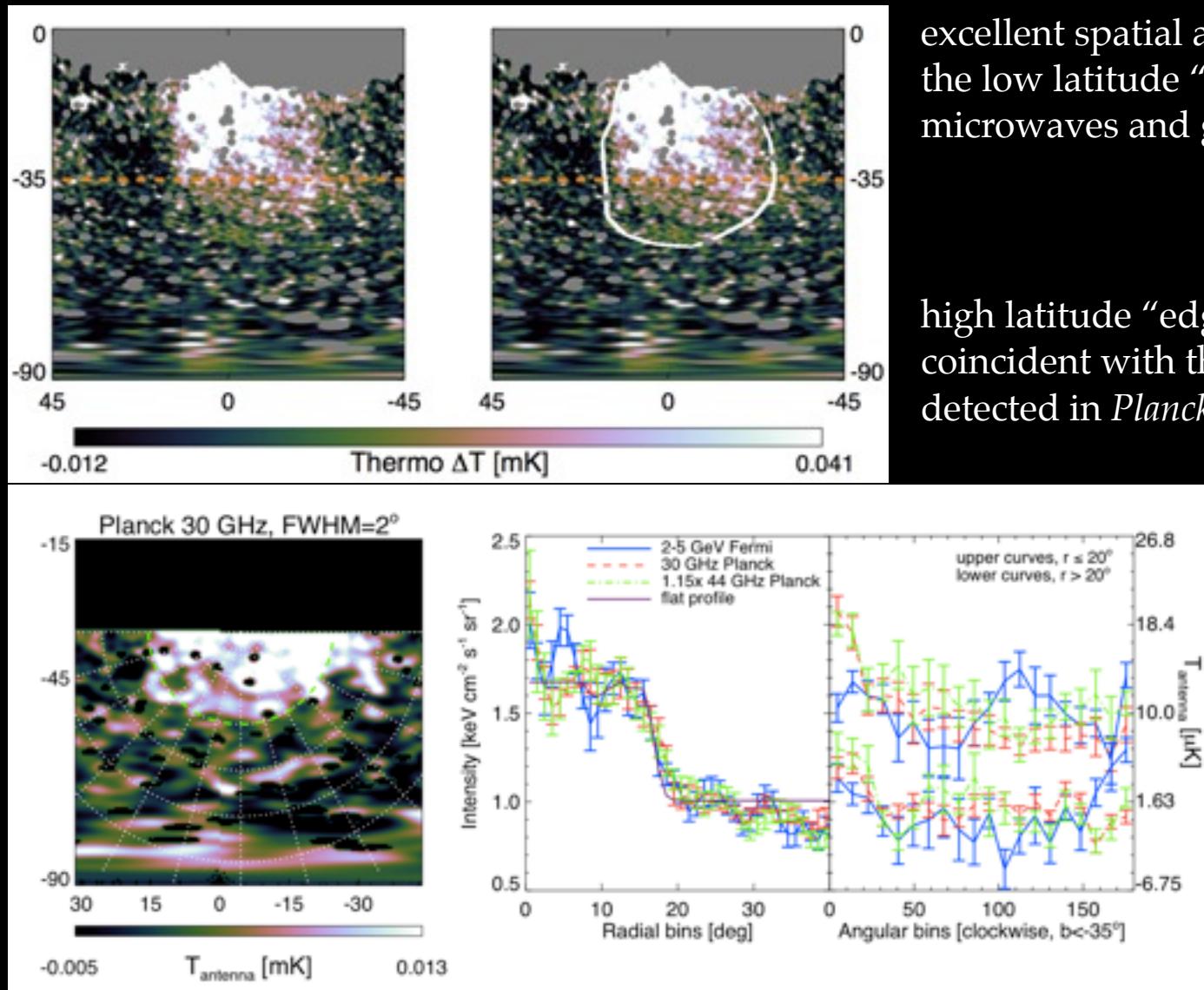
$$T_H \propto \nu^{-2.55}$$

or

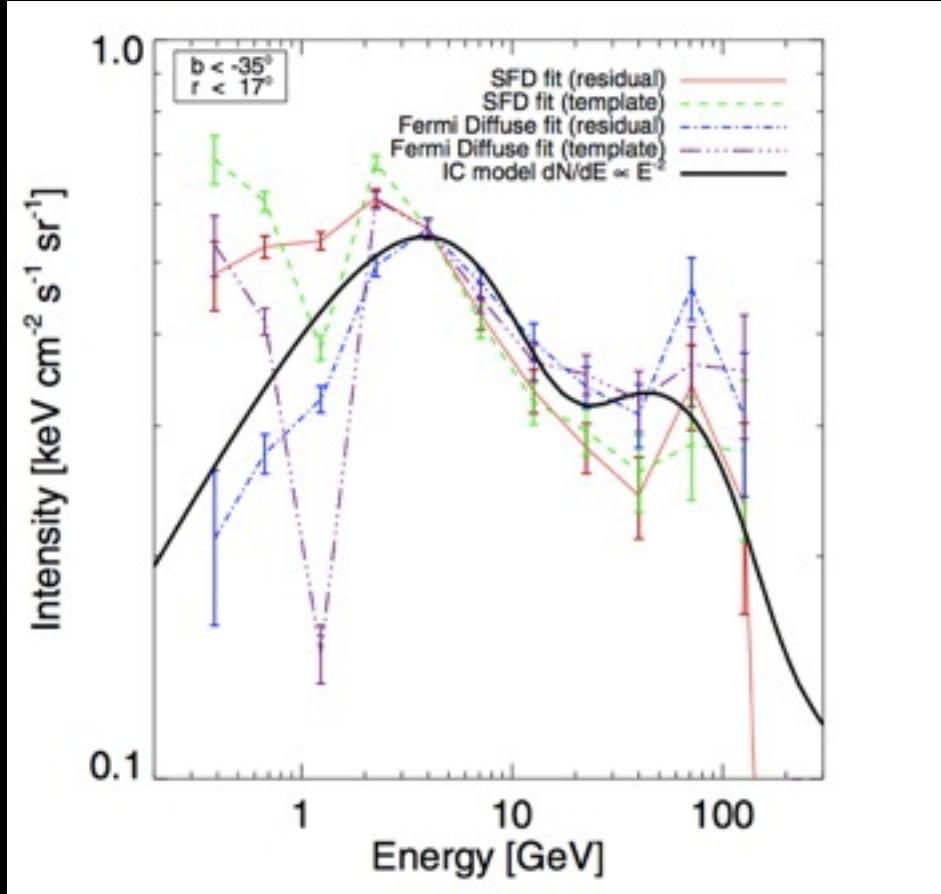
$$\frac{dN}{dE} \propto E^{-2.1}$$



Planck



measuring B-fields in radio bubbles



Dobler (2012b)

since synchrotron emissivity depends on the magnetic field strength B and the electron spectrum n_e ,

$$\text{emissivity} = j_\nu(B, n_e)$$

while the inverse Compton intensity is a function of the interstellar radiation field R and the electron spectrum n_e ,

$$\text{intensity} = I_\gamma(R, n_e)$$

we can derive an estimate of $B \sim 5 \mu\text{G}$.

what is it???

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- 1.) sharp edges plus flat profile
 - 2.) “flat” spectrum
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- 1.) seems to imply a very contrived electron distribution since constant volume emissivity gives limb-darkened profiles and shell emissivity gives limb brightened profiles.
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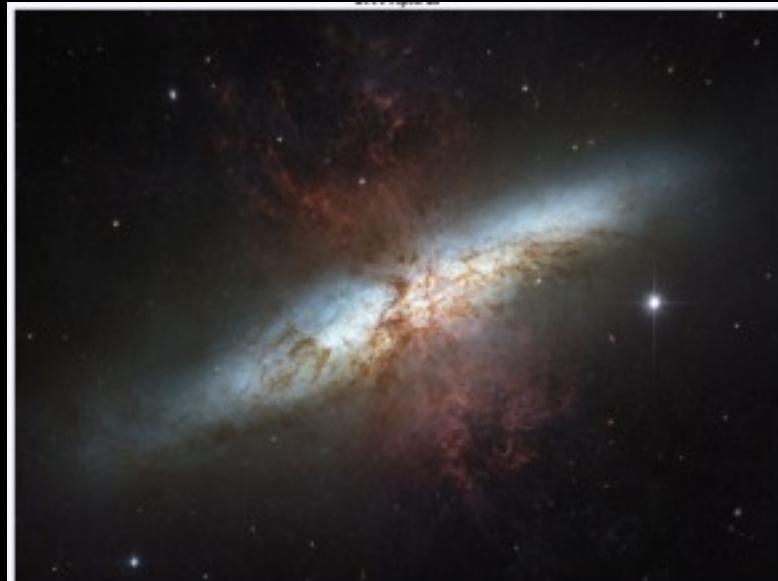
the contenders:

- wind (e.g., *Crocker & Aharonian 2011*): time scales too long, no H α , violates 1.)
- starburst: no H α , likely violates 1.) and 2.)
- AGN (e.g., *Guo & Matthews 2011*): violates 1.)
- 2nd order Fermi acc. (e.g., *Mertsch & Sarkar 2011*): violates 1.), synchrotron?
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M82: Galaxy with a Supergalactic Wind
Credit: NASA, ESA, The Hubble Heritage Team (STScI / AURA)
Acknowledgement: M. Mountain (STScI), P. Puxley (NSF), J. Gallagher (U. Wisconsin)

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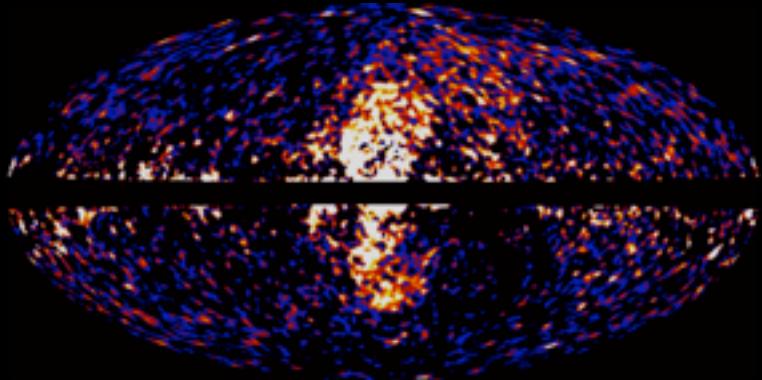
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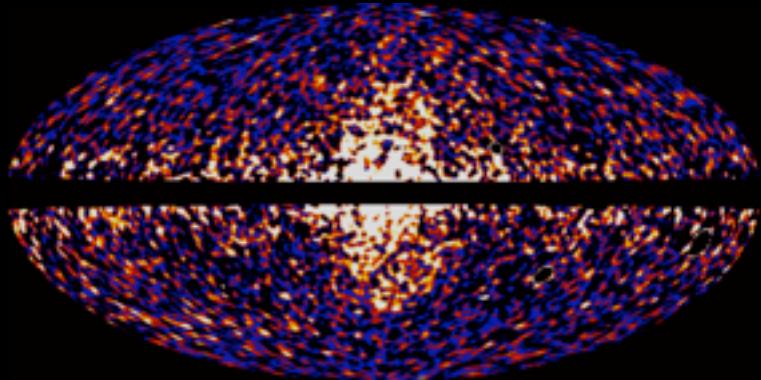
AGN jet-blown bubble

Fermi "haze/bubbles"

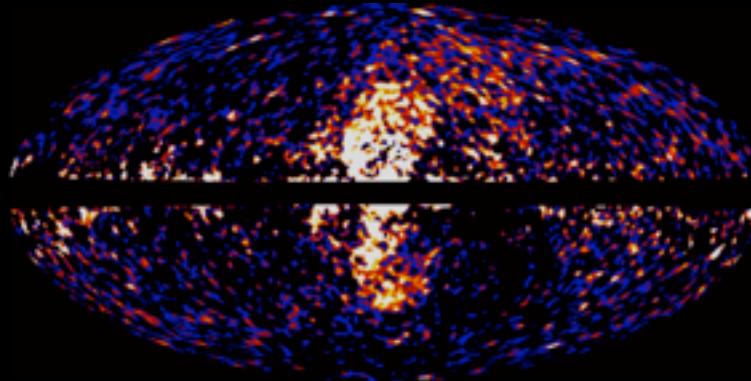


Extended source

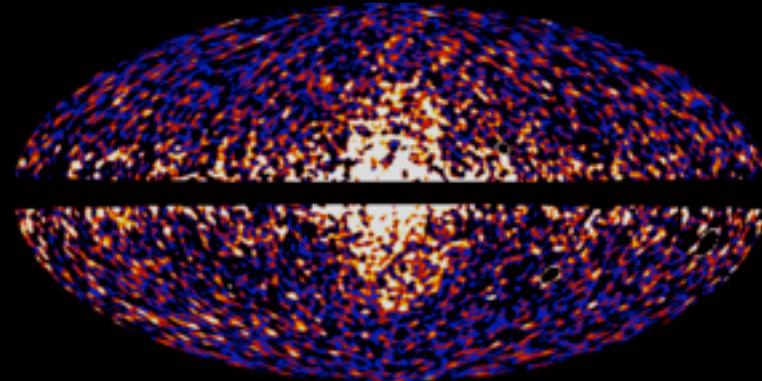
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Extended source



$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla(P + P_c) - \rho \nabla \Phi + \nabla \cdot \boldsymbol{\Pi},$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{v}) = -P\nabla \cdot \mathbf{v} + \boldsymbol{\Pi} : \nabla \mathbf{v},$$

$$\frac{\partial e_c}{\partial t} + \nabla \cdot (e_c\mathbf{v}) = -P_c\nabla \cdot \mathbf{v} + \nabla \cdot (\kappa \nabla e_c),$$

$$\frac{\partial \psi}{\partial t} = \frac{\partial(b\psi)}{\partial E} + \vec{\nabla}(D\vec{\nabla}\psi) + Q,$$

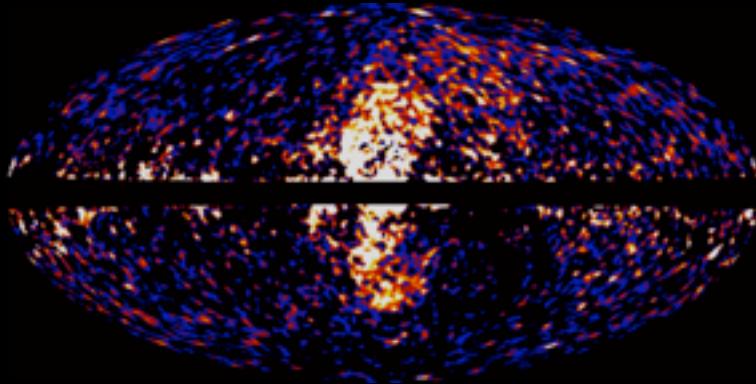
$$\begin{aligned} \vec{\nabla}(D\vec{\nabla}\psi) = & \frac{1}{r} \frac{\partial}{\partial r} (r D_{rr} \frac{\partial \psi}{\partial r} + r D_{rz} \frac{\partial \psi}{\partial z}) \\ & + \frac{\partial}{\partial z} (D_{zz} \frac{\partial \psi}{\partial z} + D_{zr} \frac{\partial \psi}{\partial r}), \end{aligned}$$

$$D_{ij} = D_0 \left(\frac{\nu^2 \delta_{ij} + \Omega_i \Omega_j}{\nu^2 + \Omega^2} \right),$$

$$Q(r, z) = \frac{1}{2} \langle \sigma v \rangle \frac{dN}{dE} \left(\frac{\rho(r, z)}{M_\chi} \right)^2,$$

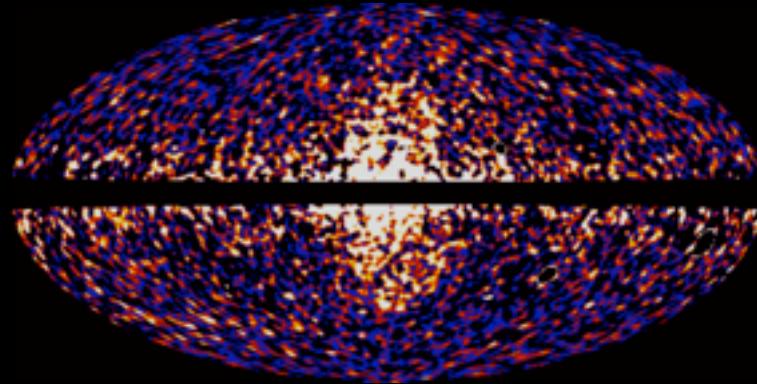
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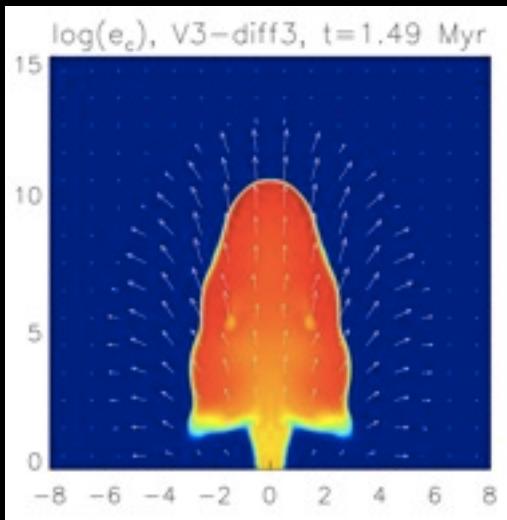


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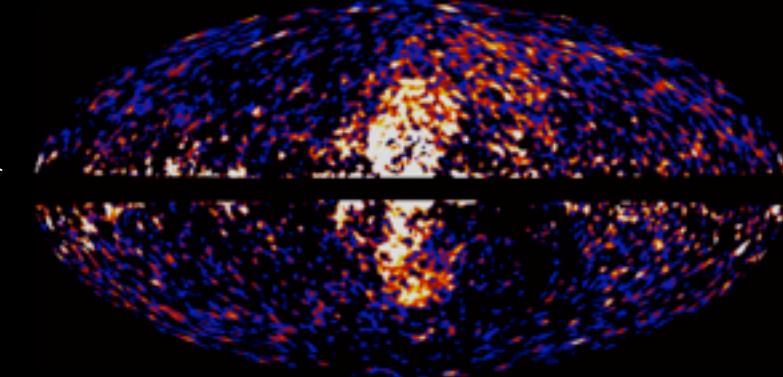


Guo, Matthews, Dobler, & Oh (2011)



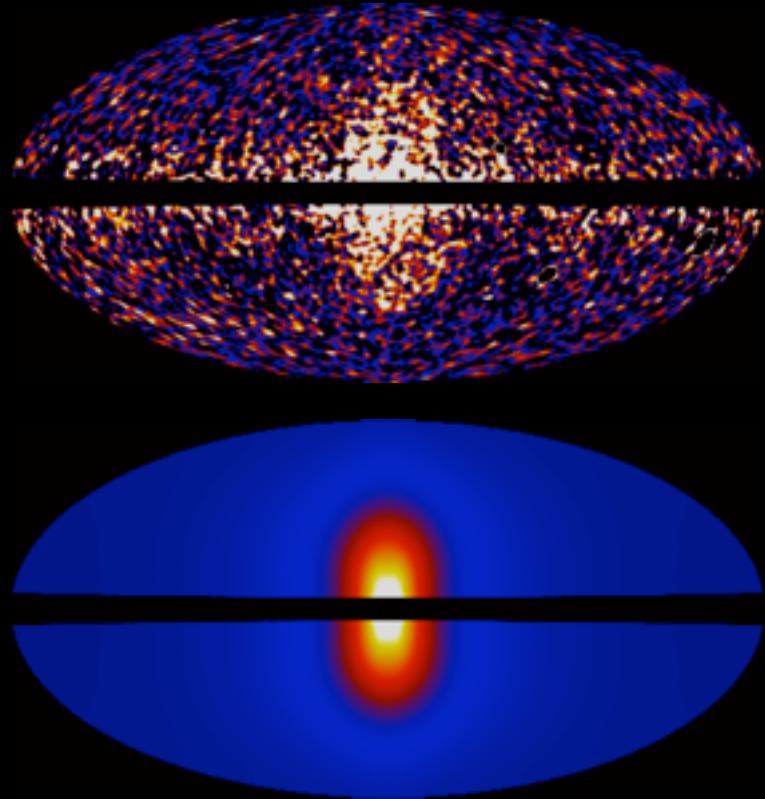
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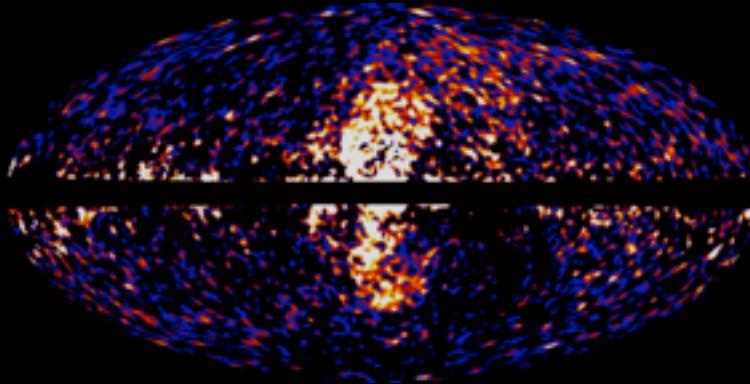
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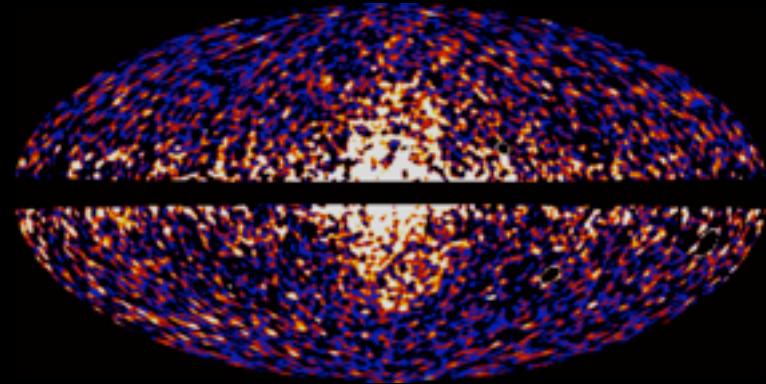
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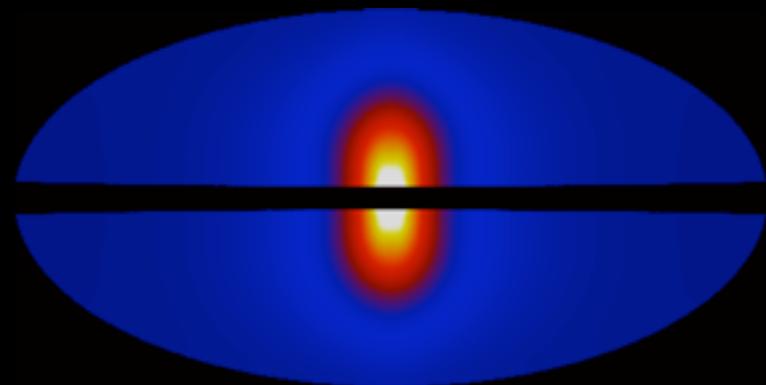
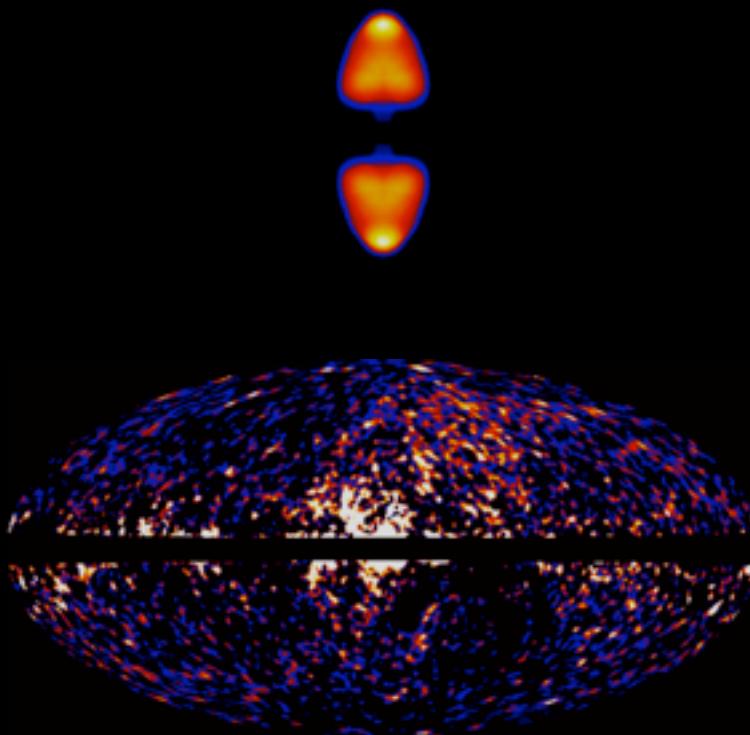


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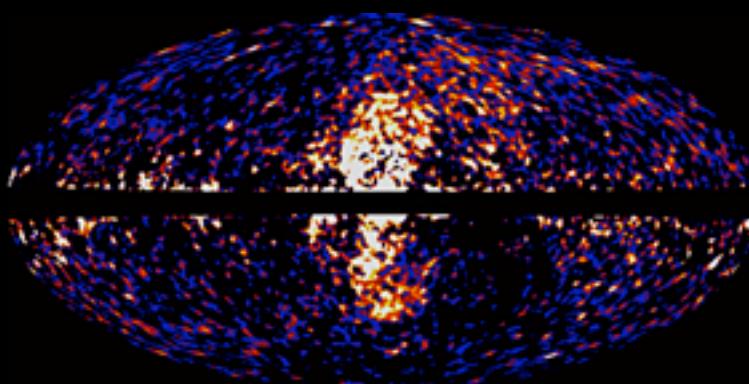
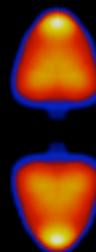
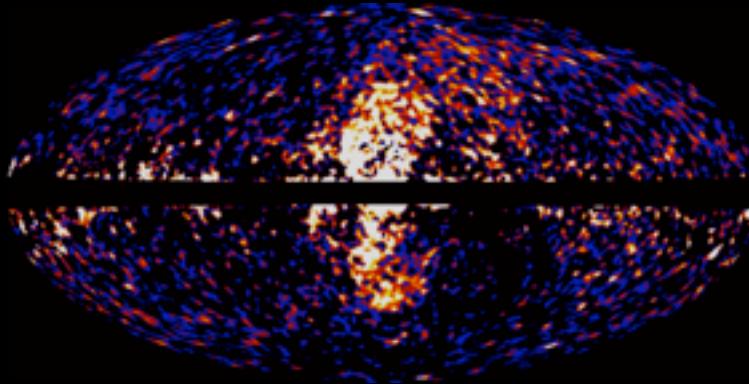
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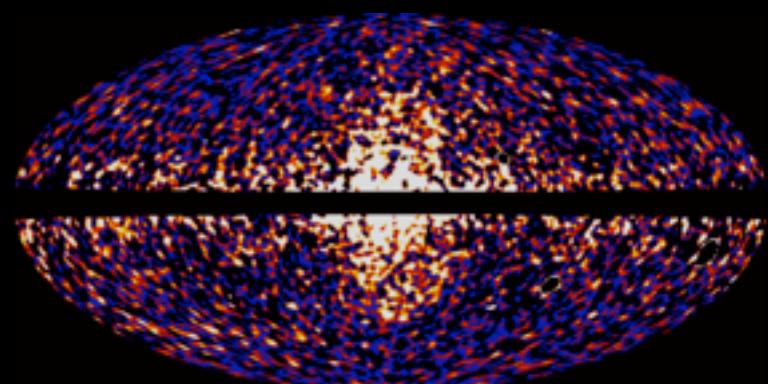
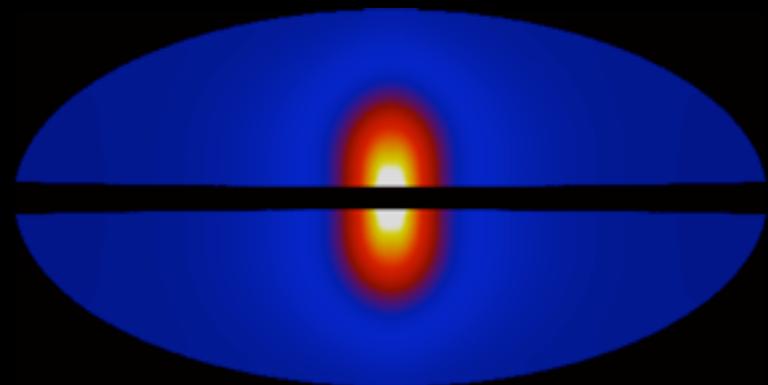
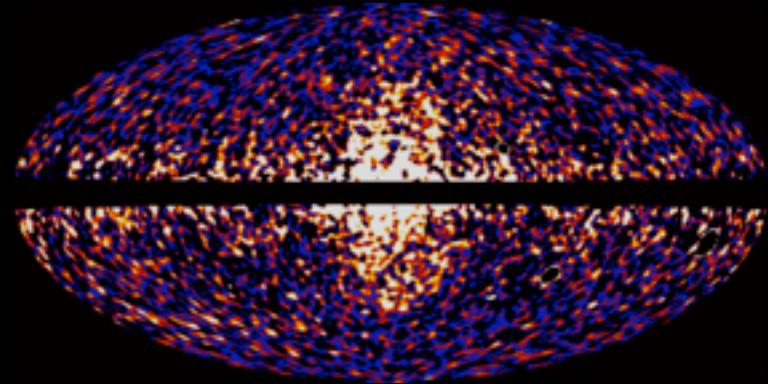
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many puzzles...

but may opportunities!

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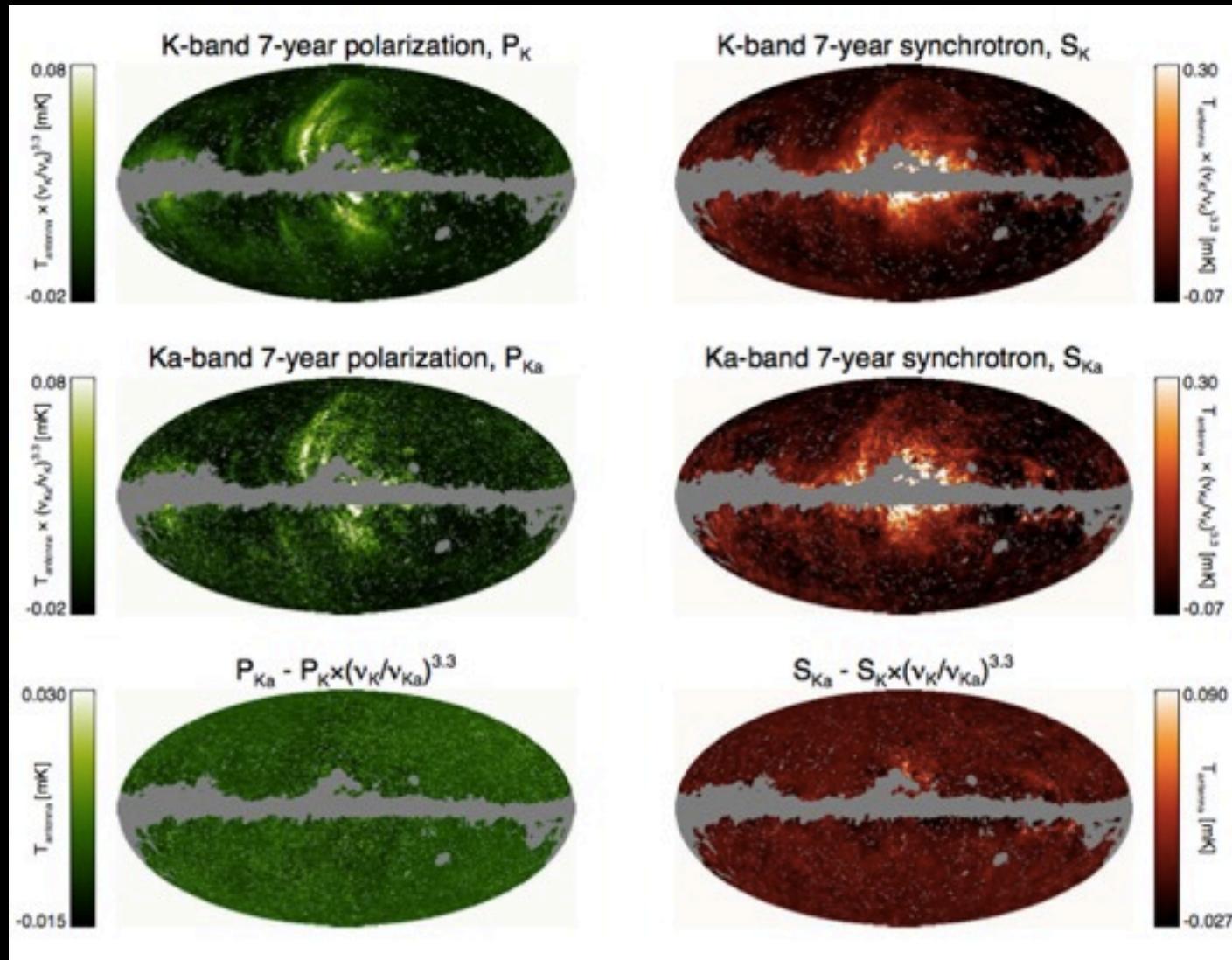
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polarization



Dobler (2012a)

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